Jet Mixing Noise Scaling Laws
SHJAR Data vs. Pridictions

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Abstract:
High quality jet noise spectral data measured at the anechoic dome at the NASA Glenn Research Center is used to examine a number of jet noise scaling laws. Configurations considered in the present study consist of convergent as well as convergent-divergent axisymmetric nozzles. The spectral measurements are shown in narrow band and cover 8193 equally spaced points in a typical Strouhal number range of (0.01 – 10.0). Measurements are reported as lossless (i.e. atmospheric attenuation is added to as-measured data), and at 24 equally spaced angles (50o to 165o) on a 100-diameter arc.

Following the work of Viswanathan [Ref. 1], velocity power laws are derived using a least square fit on spectral power density as a function of jet temperature and observer angle. The goodness of the fit is studied at each angle, and alternative relationships are proposed to improve the spectral collapse when certain conditions are met. On the application side, power laws are extremely useful in identifying components from various noise generation mechanisms. From this analysis, jet noise prediction tools can be developed with physics derived from the different spectral components.

JET MIXING NOISE SCALING LAWS
SHJAR DATA vs. PREDICTIONS

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Acoustic Technical Working Group
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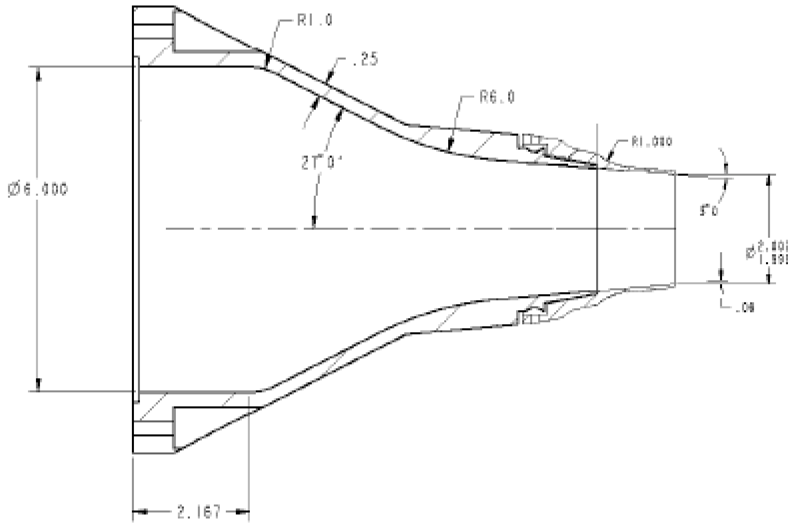
Overview

- Scaling Laws – SHJAR data
  - Sideline Angles
  - Small Aft Angles
  - Noise Components (Mixing, Shock, Screech, AMN)

- JeNo Scaling (unheated jets)

Acoustic Dome

SHJAR within the Dome



2-in convergent nozzle smc000

Bridges, *et al.* AIAA-2005-2846

AIAA-2007-3628

SHJAR 2-in SINGLE FLOW NOZZLES

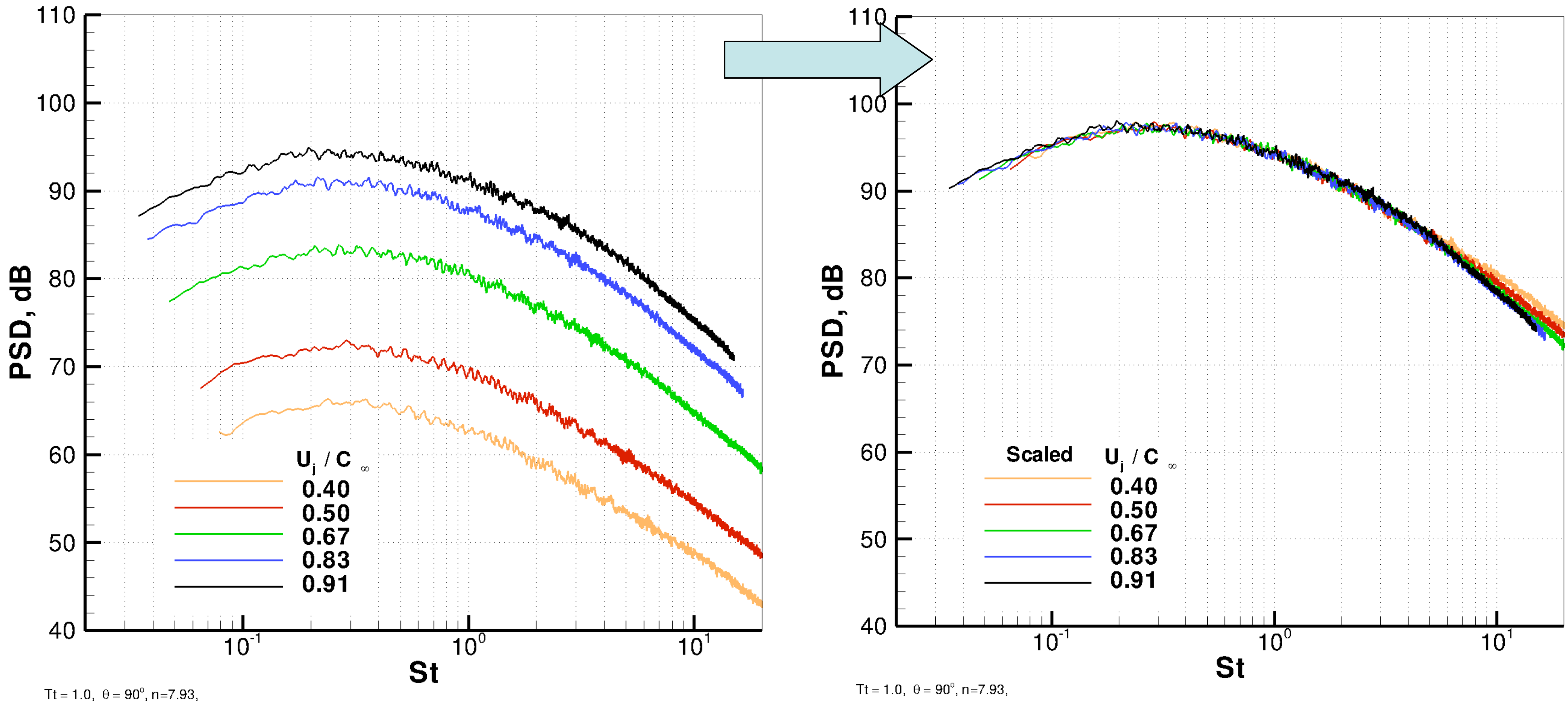
Nozzle	Configuration	Design Mach	Diameter inches	Design NPR
smc000	Convergent	1.00	2.0	1.89
smc021*	Convergent	1.00	2.0	1.89
smc014	CD	1.185	2.0	2.37
smc015	CD	1.40	2.0	3.18
smc016	CD	1.50	2.0	3.67
smc018	CD	1.80	2.0	5.74

* Screech free

All data shown in NB, lossless and on ARC = 100D

POWER LAW $U^{n(\theta,T)}$

$$T_t = 1.0, \quad \theta = 90^o$$



$$St = fD / U_j$$

$$PSD = 10 Log(\overline{p^2} U_j / p_{ref}^2 D)$$

$$PSD\,(\text{Scaled}) = PSD - 10n(\theta,T) Log(U_j / c_\infty)$$

POWER LAW (Least-Square Method)

$$\hat{y}_i = OASPL(\theta, T), \quad i = 1, 2, \ldots, N$$

Viswanathan, K., AIAA J. 44(10), 2006

$$y_i = n(\theta, T)\, x_i + B(\theta, T); \quad x_i = 10\, Log(U_i / c_\infty), \quad i = 1, 2, \ldots, N$$

Power factor

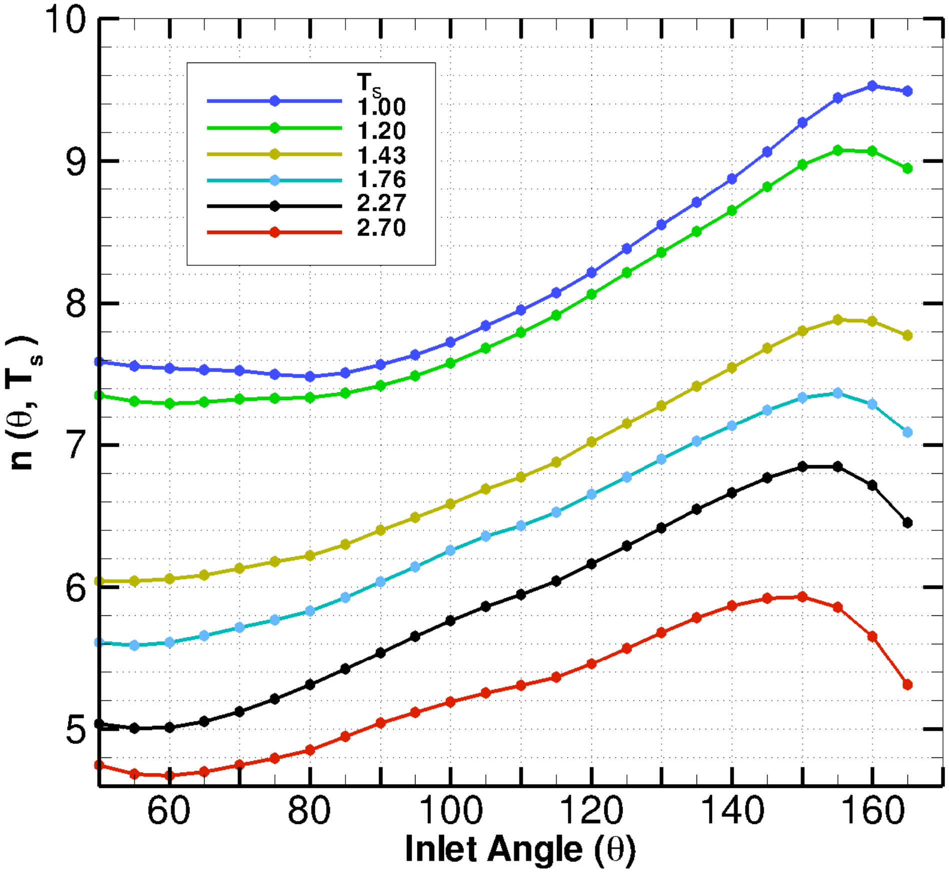
Intercept parameter

$$\chi(\theta, T) = \frac{1}{N-2} \sum_{i=1}^{N} \frac{(\hat{y}_i - y_i)^2}{\sigma_i}$$

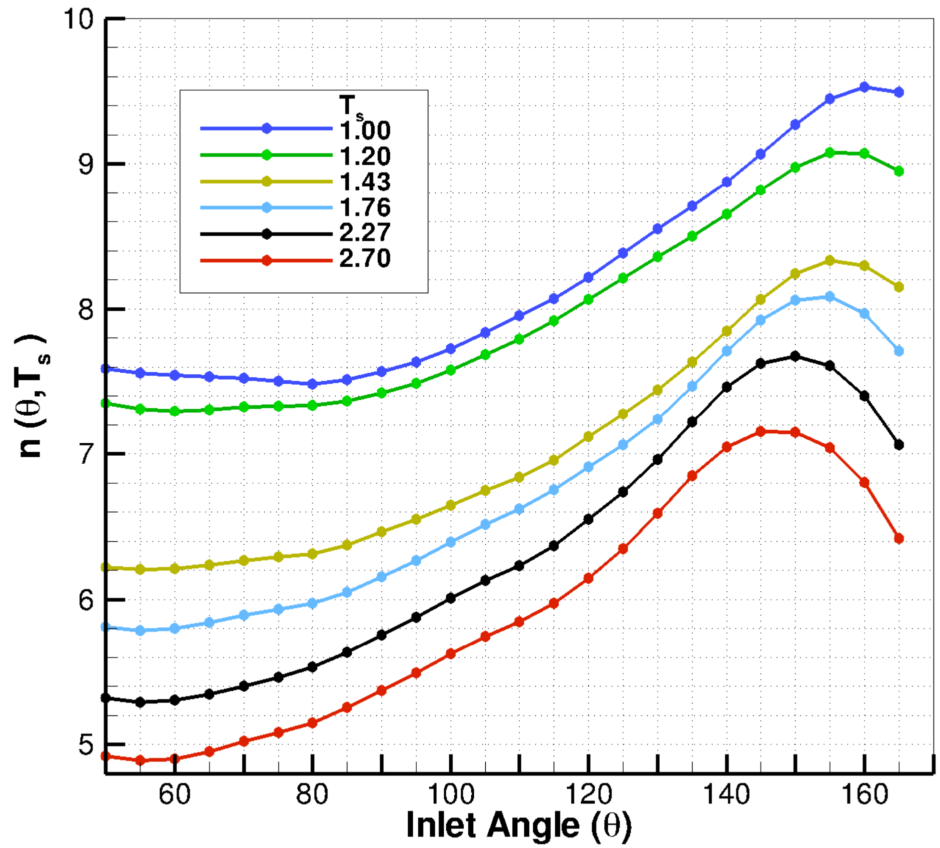
Goodness Factor

VELOCITY POWER FACTOR - *n* (Constant Static Temp)

Excludes points at $U_j / c_\infty > 1.0$

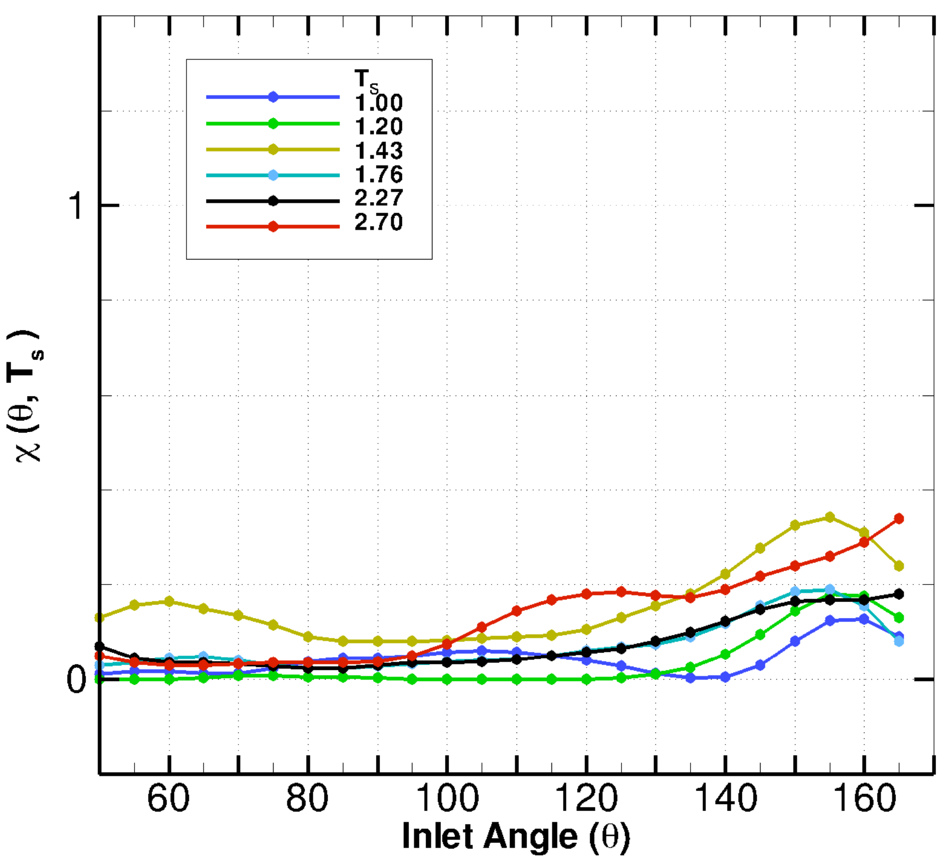


Includes points at $U_j / c_\infty > 1.0$

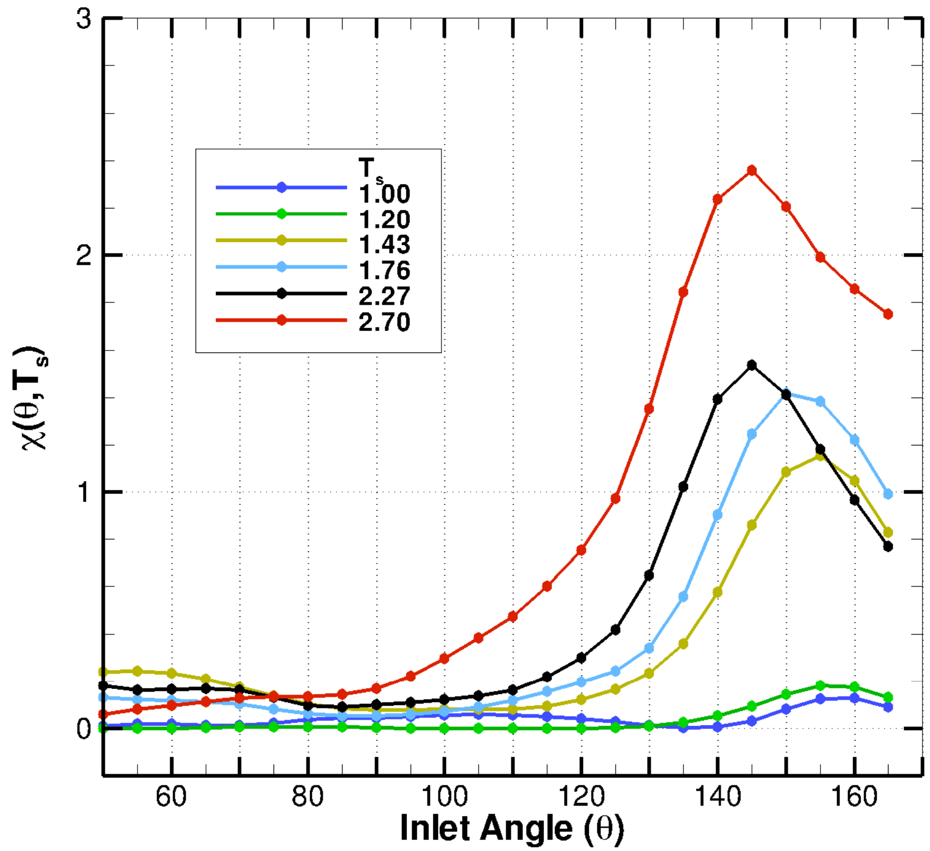


GOODNESS FACTOR
(Constant Static Temp)

Excludes points at $U_j / c_\infty > 1.0$

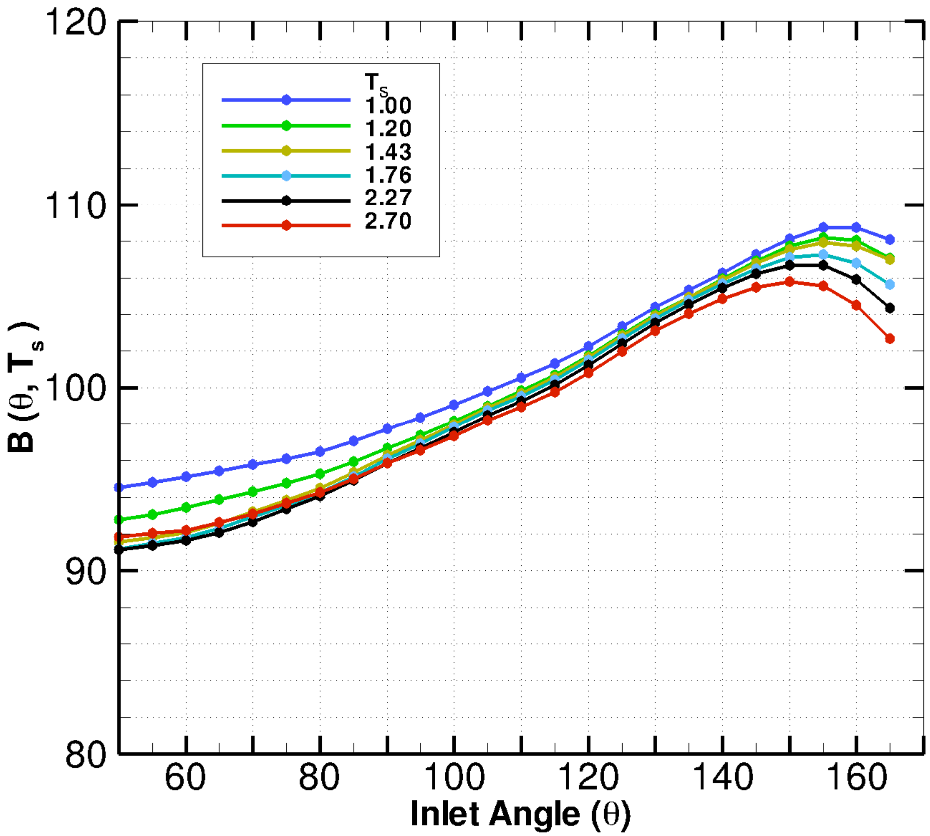


Includes points at $U_j / c_\infty > 1.0$

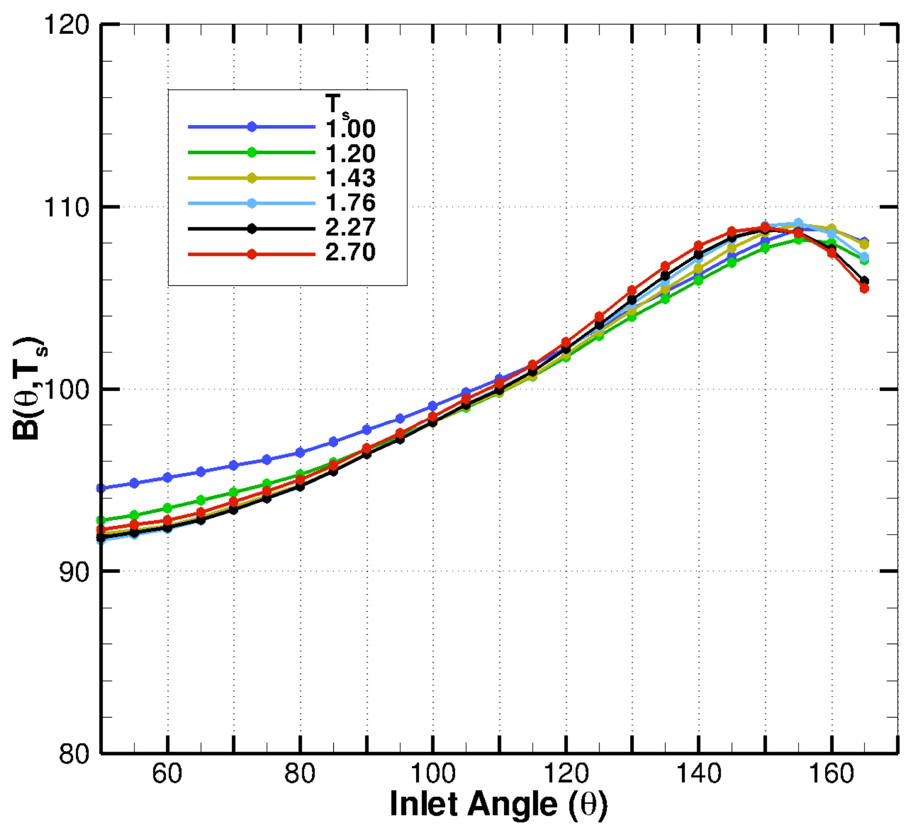


INTERCEPT PARAMETER (Contact Static Temp)

Excludes points at $U_j / c_\infty > 1.0$



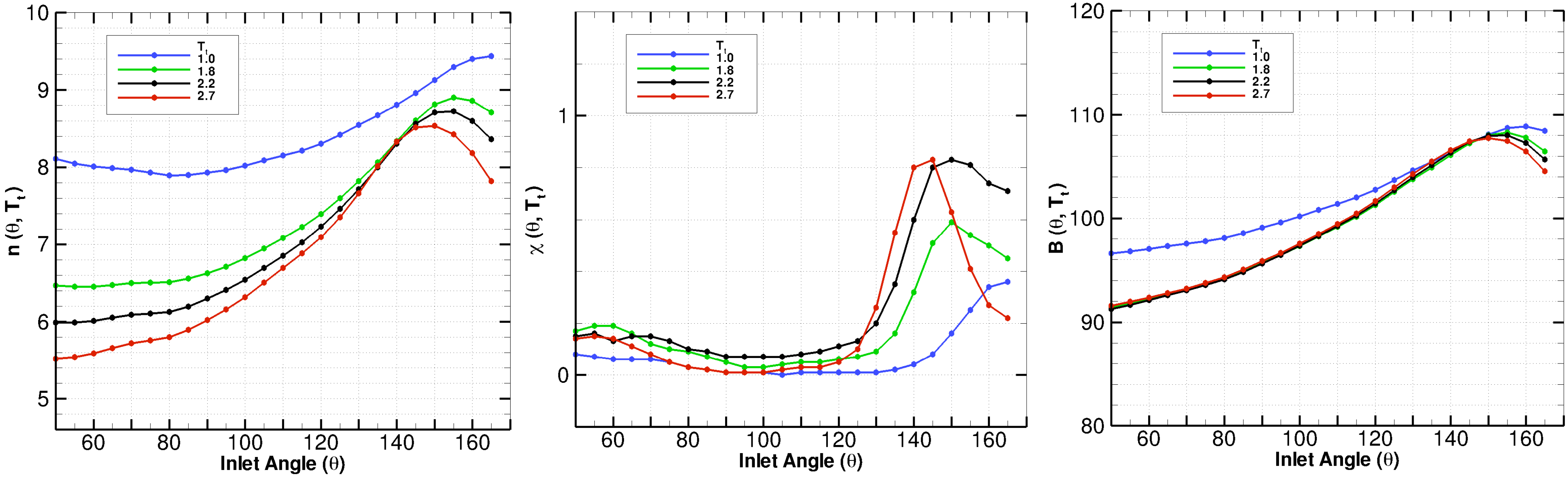
Includes points at $U_j / c_\infty > 1.0$



POWER LAW
(Constant Total Temp)

Tt
1.0
1.8
2.2
2.7

Includes points at $U_j / c_\infty > 1.0$



- ➢ Power law deteriorates at small aft angles
- ➢ Unheated jets have a distinctly different intercept parameter

APPLICATION OF POWER LAW (Noise Components)

FULLY EXPANDED VALUES

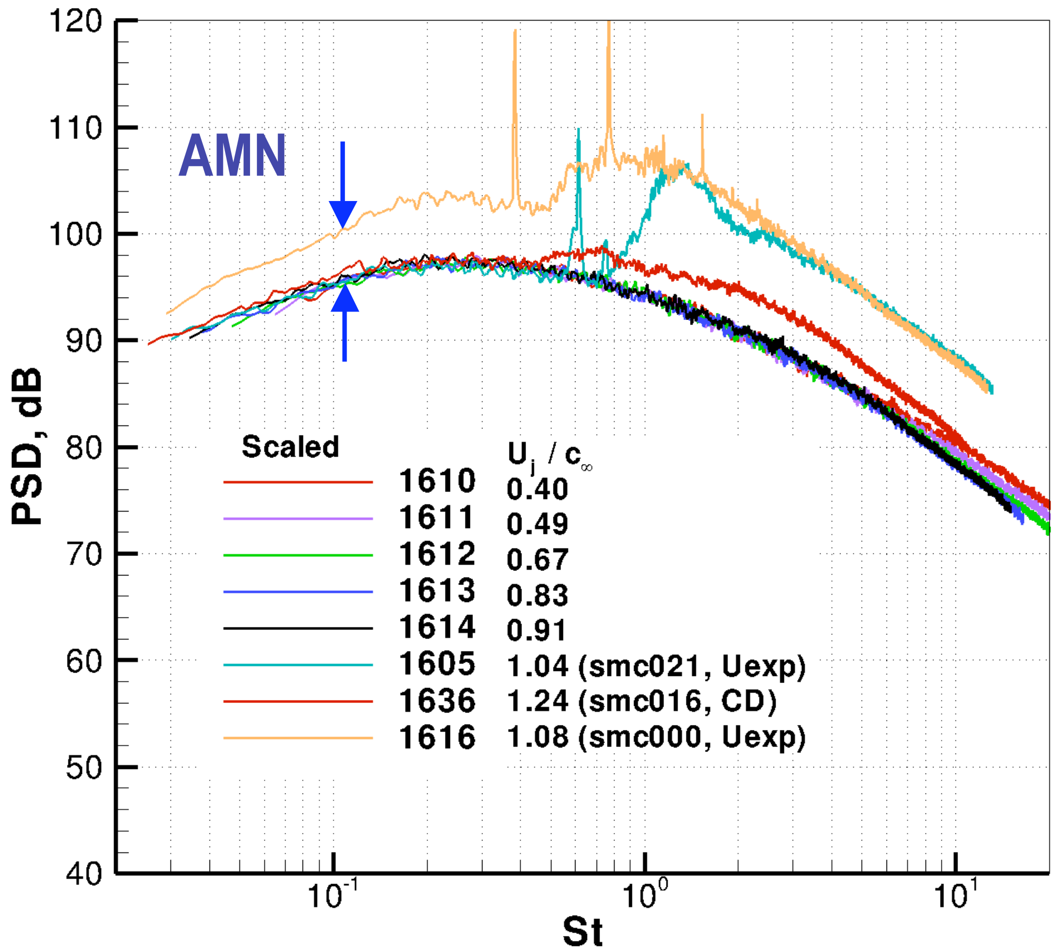
$$PSD(\text{Scaled}) = PSD - 10n(\theta,T)Log(U_j / c_\infty) - 10Log(A_j / A_e)$$

Table C. SHJAR readings at plenum temperature ratio 1. 0

	Rdg	Nozzle	T_s	T_t	U_j / c_∞	M	NPR	M_j	A_j / A_e
	1610	smc000	0.97	1.0	0.40	0.40	1.117	0.40	1.0
	1611		0.96	1.0	0.49	0.50	1.186	0.50	1.0
	1612		0.91	1.0	0.67	0.70	1.387	0.70	1.0
	1613		0.86	1.0	0.83	0.90	1.692	0.90	1.0
	1614		0.83	1.0	0.91	1.00	1.893	1.00	1.0
	1616		0.76	1.0	1.08	1.00	2.556	1.24	1.043
	1618		0.70	1.0	1.23	1.00	3.514	1.47	1.156
CD	1636	smc016	0.69	1.0	1.24	1.50	3.671	1.50	1.0
Screech-free	1605	smc021	0.80	1.02	1.04	1.00	2.328	1.17	1.02

SCALED SPECTRA

$$T_r = 1, \theta = 90^o, n = 7.93$$



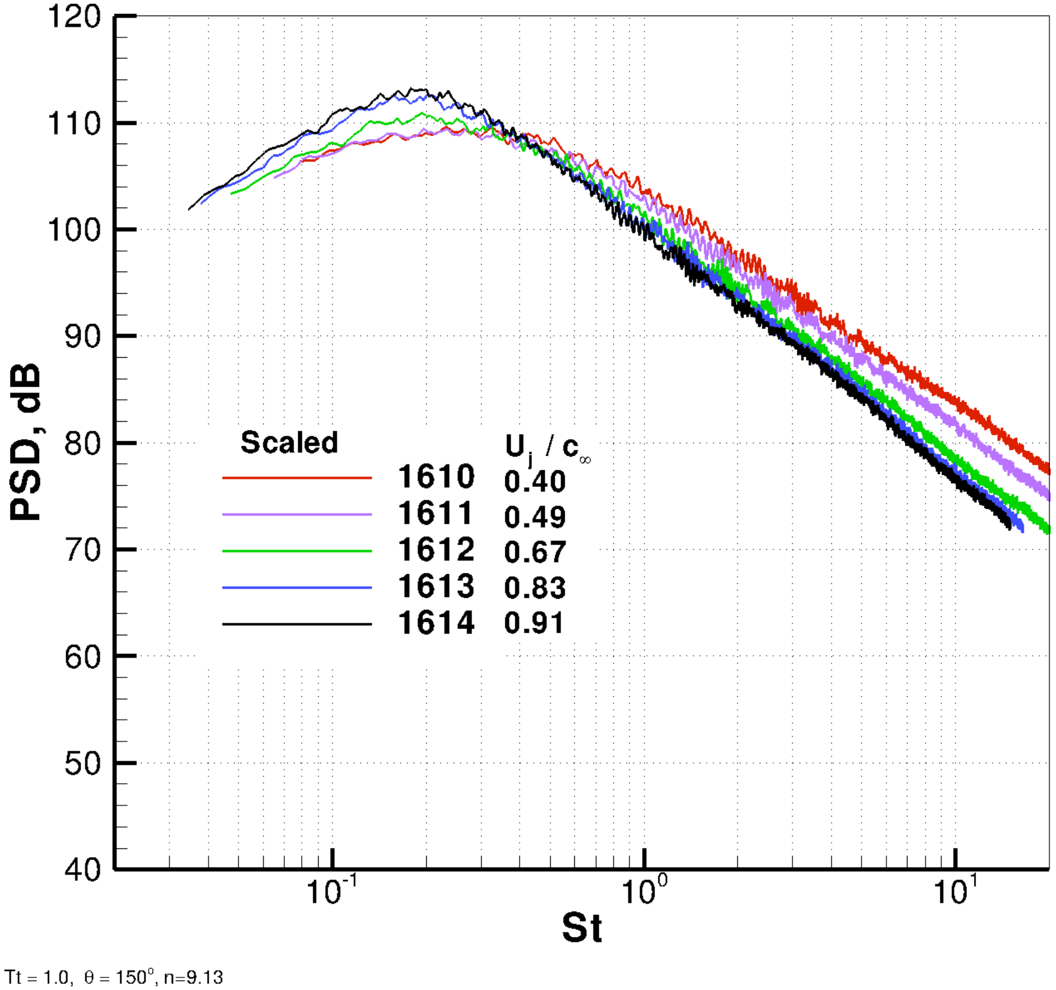
Tt = 1.0, θ = 90°, n=7.93

AMN:

Amplification of mixing noise due to screech

SCALED SPECTRA

$$T_r = 1, \theta = 150^o, n = 9.13$$

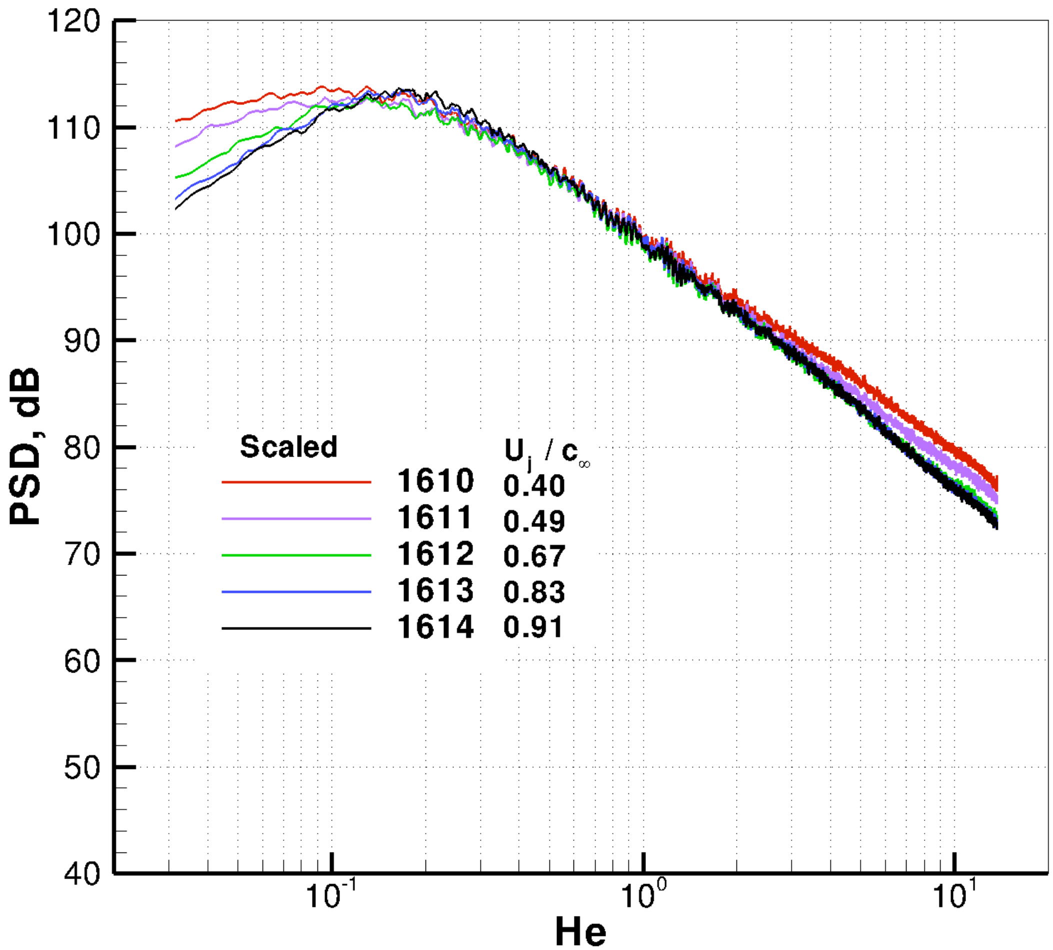


smc000

Rdg	U_j/c_∞	M	NPR
1610	0.40	0.40	1.11
1611	0.49	0.50	1.18
1612	0.67	0.70	1.38
1613	0.83	0.90	1.69
1614	0.91	1.0	1.89

SCALED SPECTRA

$$T_r = 1, \theta = 150^o, n = 10.20$$



Tt = 1.0, θ = 150°, n=10.20

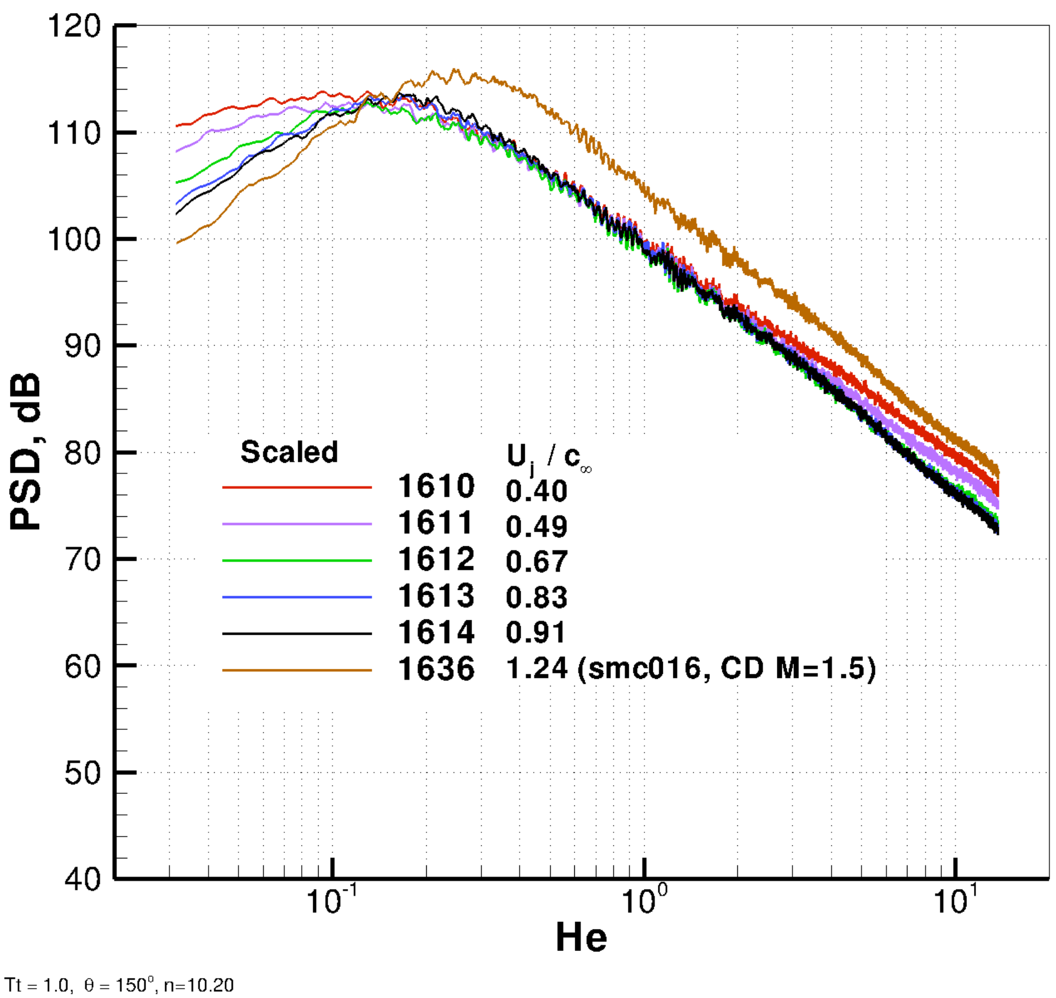
- Freq parameter (He)
- Adjust power factor (9.13 --> 10.20)

$$He = f\, D / c_\infty$$

Rdg	U_j/c_∞	M	NPR
1610	0.40	0.40	1.11
1611	0.49	0.50	1.18
1612	0.67	0.70	1.38
1613	0.83	0.90	1.69
1614	0.91	1.0	1.89

SCALED SPECTRA

$$T_r = 1, \theta = 150^o, n = 10.20$$

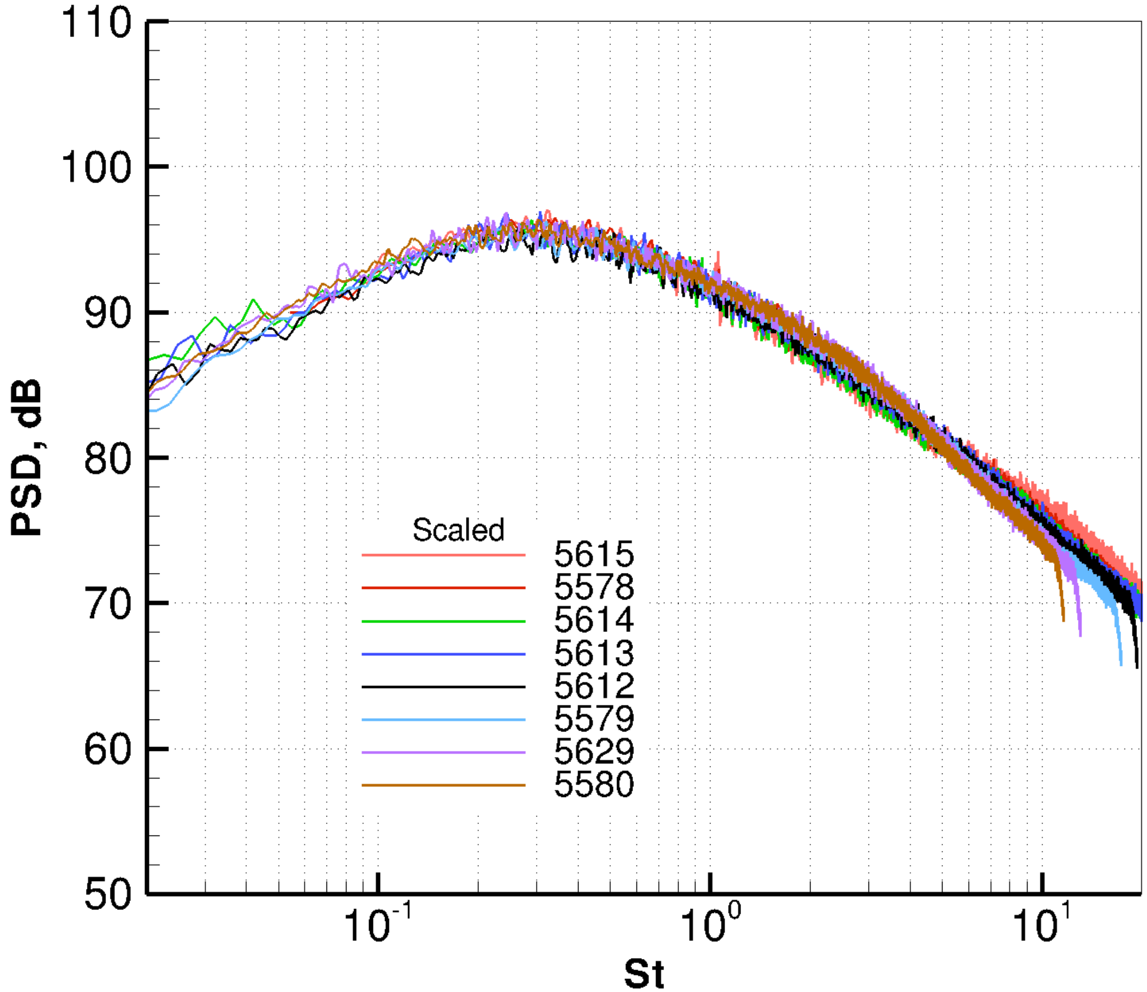


Mach 1.50 CD nozzle

Rdg	U_j/c_∞	M	M_j	NPR
1636 smc016	1.24	1.50	1.50	3.67

SCALED SPECTRA

$$T_s = 1.76, \theta = 90^o, n = 6.15$$



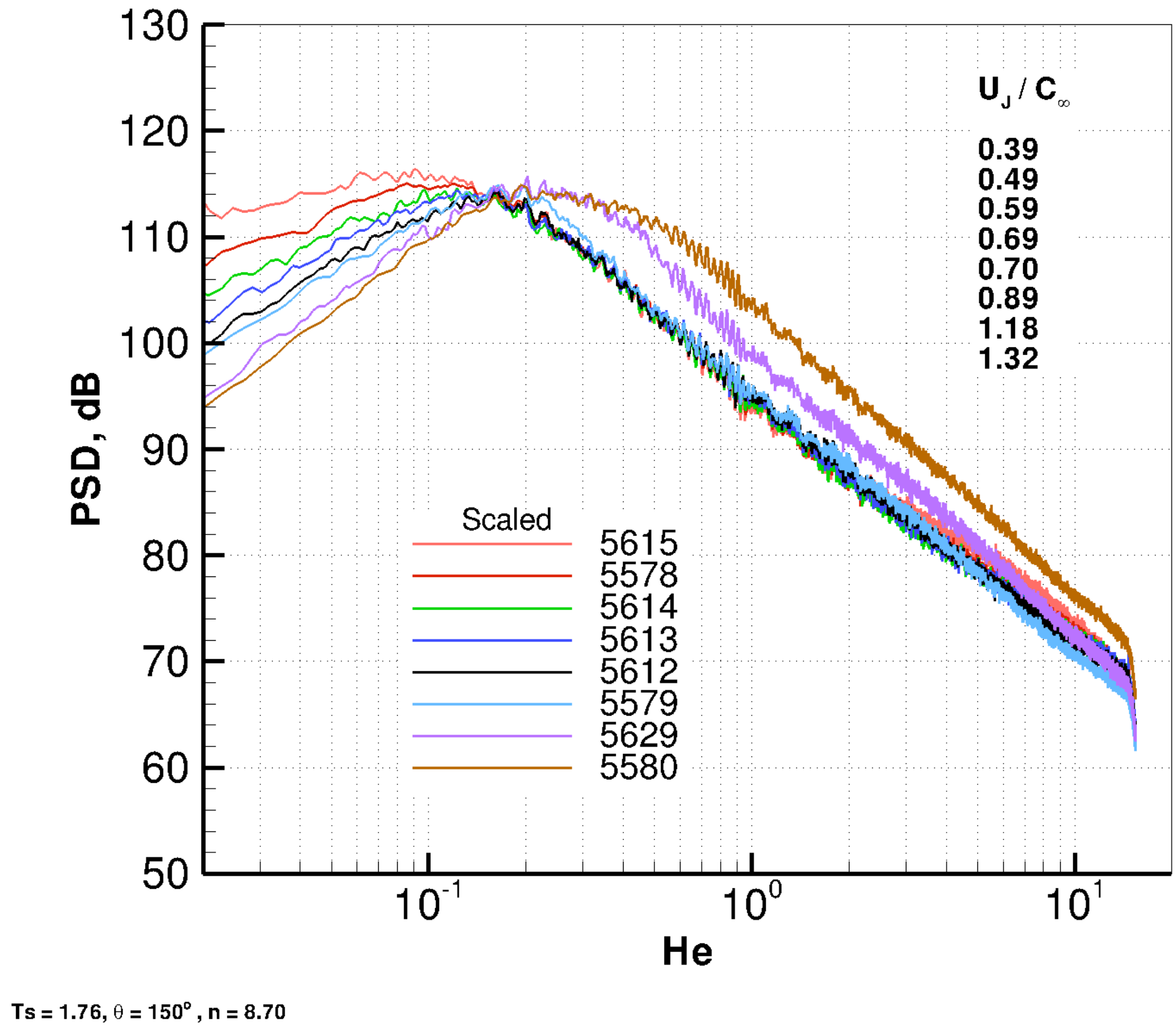
Ts = 1.76, θ = 90°, n = 6.15

smc000

Rdg	U_j/c_∞	M	NPR
5615	0.39	0.29	1.06
5578	0.49	0.37	1.10
5614	0.59	0.45	1.14
5613	0.69	0.52	1.20
5612	0.79	0.60	1.27
5579	0.89	0.67	1.35
5629	1.18	0.89	1.67
5580	1.32	1.0	1.89

SCALED SPECTRA

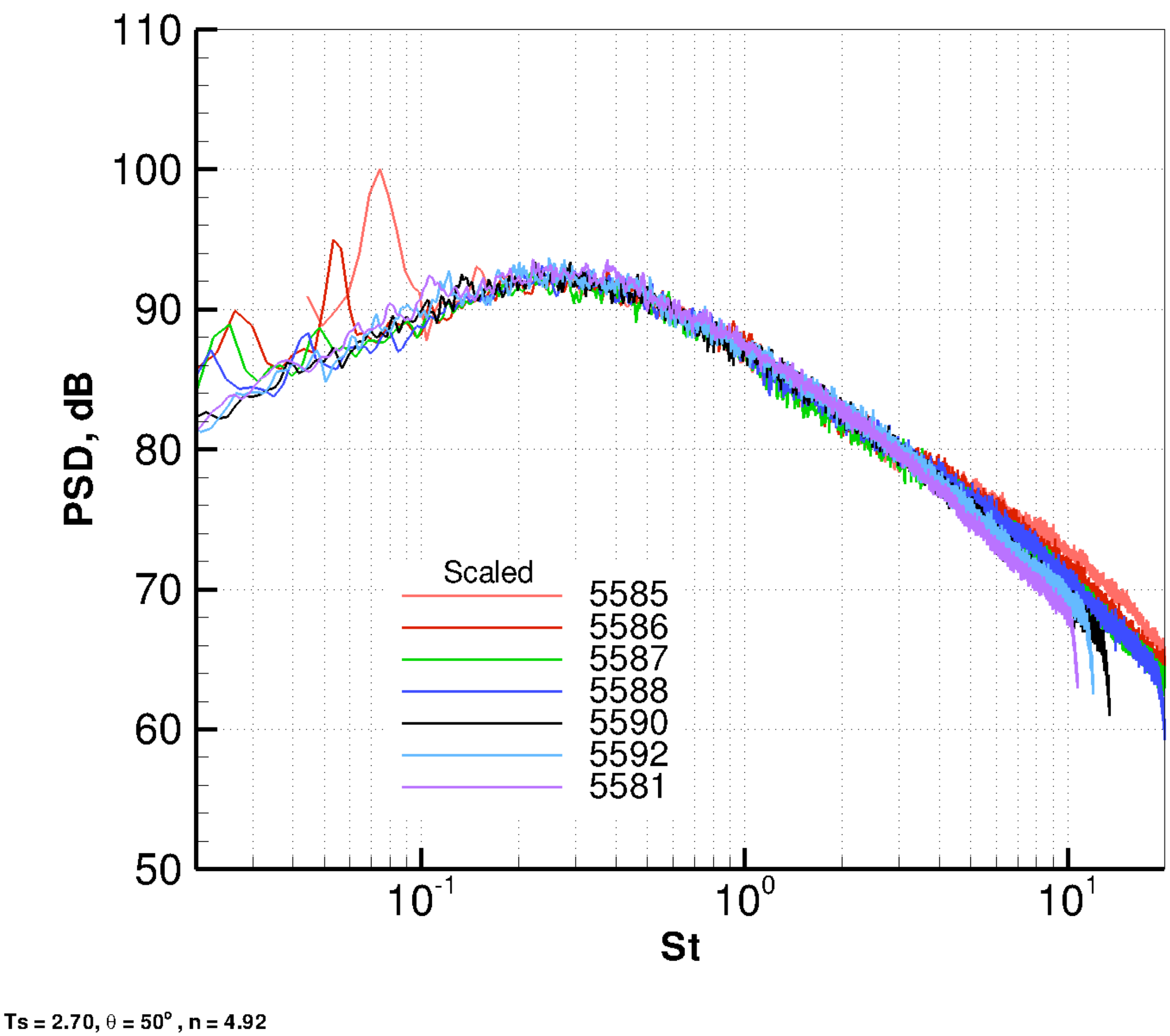
$$T_s = 1.76, \theta = 150^o, n = 8.70$$



Rdg	U_j/c_∞	M	NPR
5615	0.39	0.29	1.06
5578	0.49	0.37	1.10
5614	0.59	0.45	1.14
5613	0.69	0.52	1.20
5612	0.79	0.60	1.27
5579	0.89	0.67	1.35
5629	1.18	0.89	1.67
5580	1.32	1.0	1.89

SCALED SPECTRA

$$T_s = 2.70, \theta = 50^o, n = 4.92$$

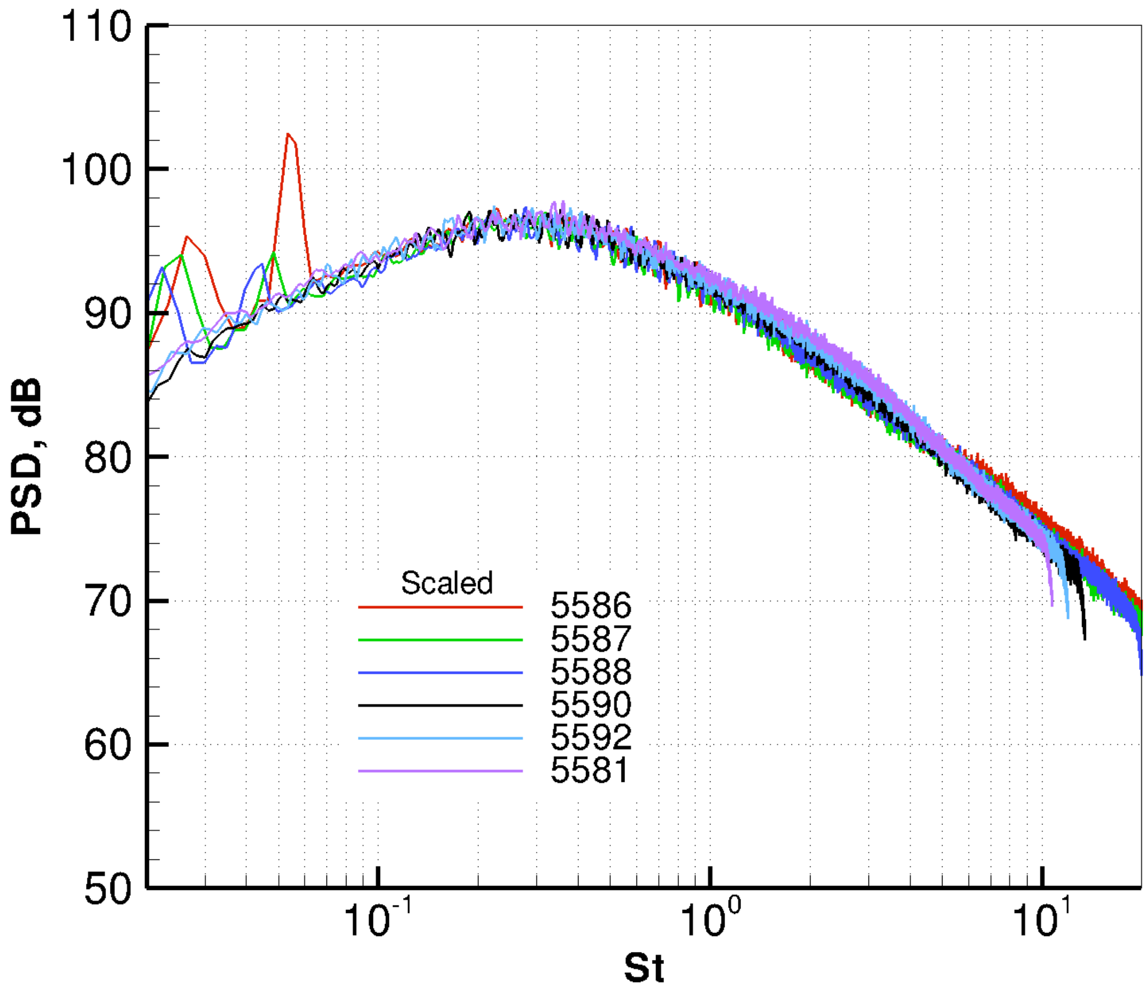


smc000

Rdg	U_j/c_∞	M	NPR
5585	0.39	0.24	1.04
5585	0.59	0.36	1.09
5587	0.69	0.42	1.12
5588	0.79	0.48	1.17
5590	1.17	0.72	1.40
5592	1.32	0.81	1.52
5581	1.47	0.91	1.69

SCALED SPECTRA

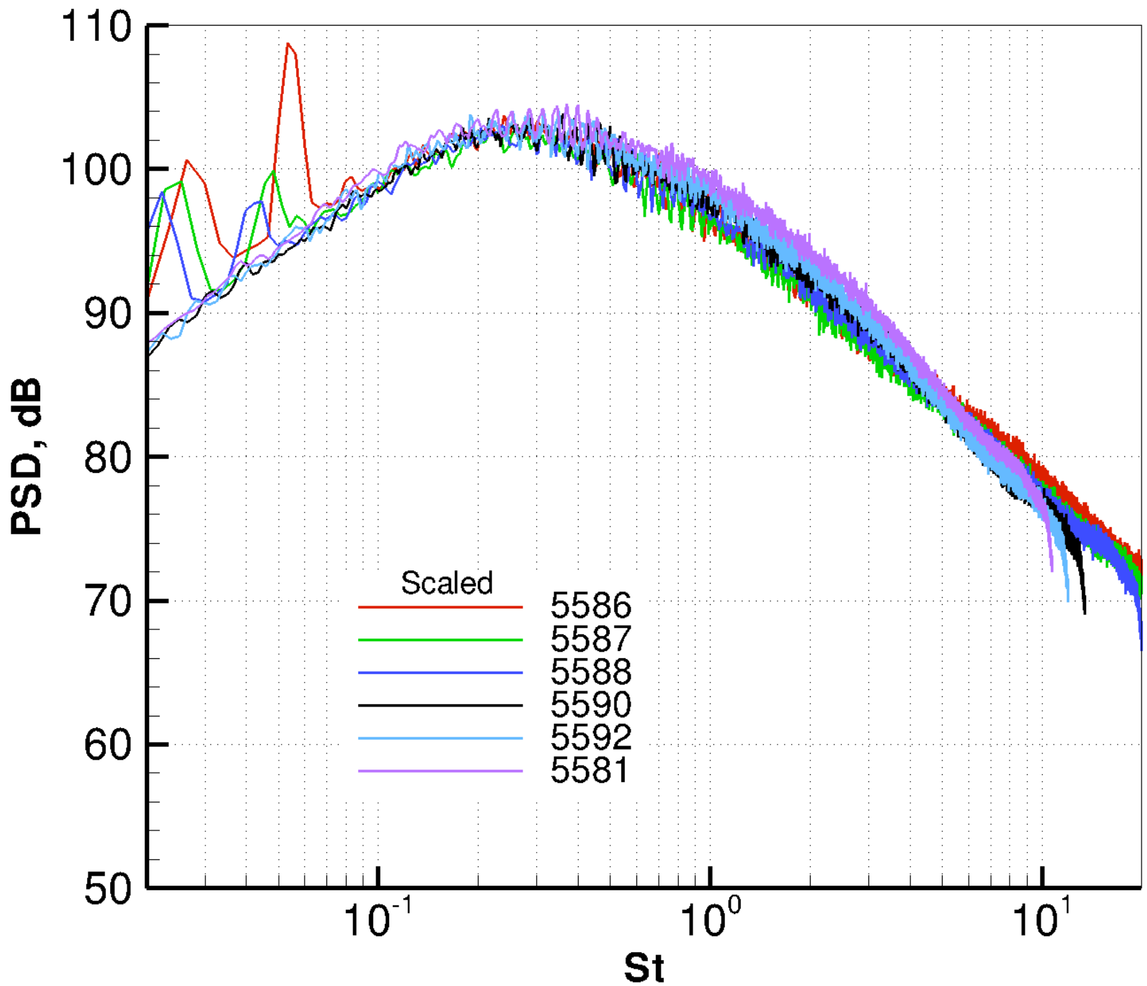
$$T_s = 2.70, \theta = 90^o, n = 5.37$$



Ts = 2.70, θ = 90°, n = 5.37

SCALED SPECTRA

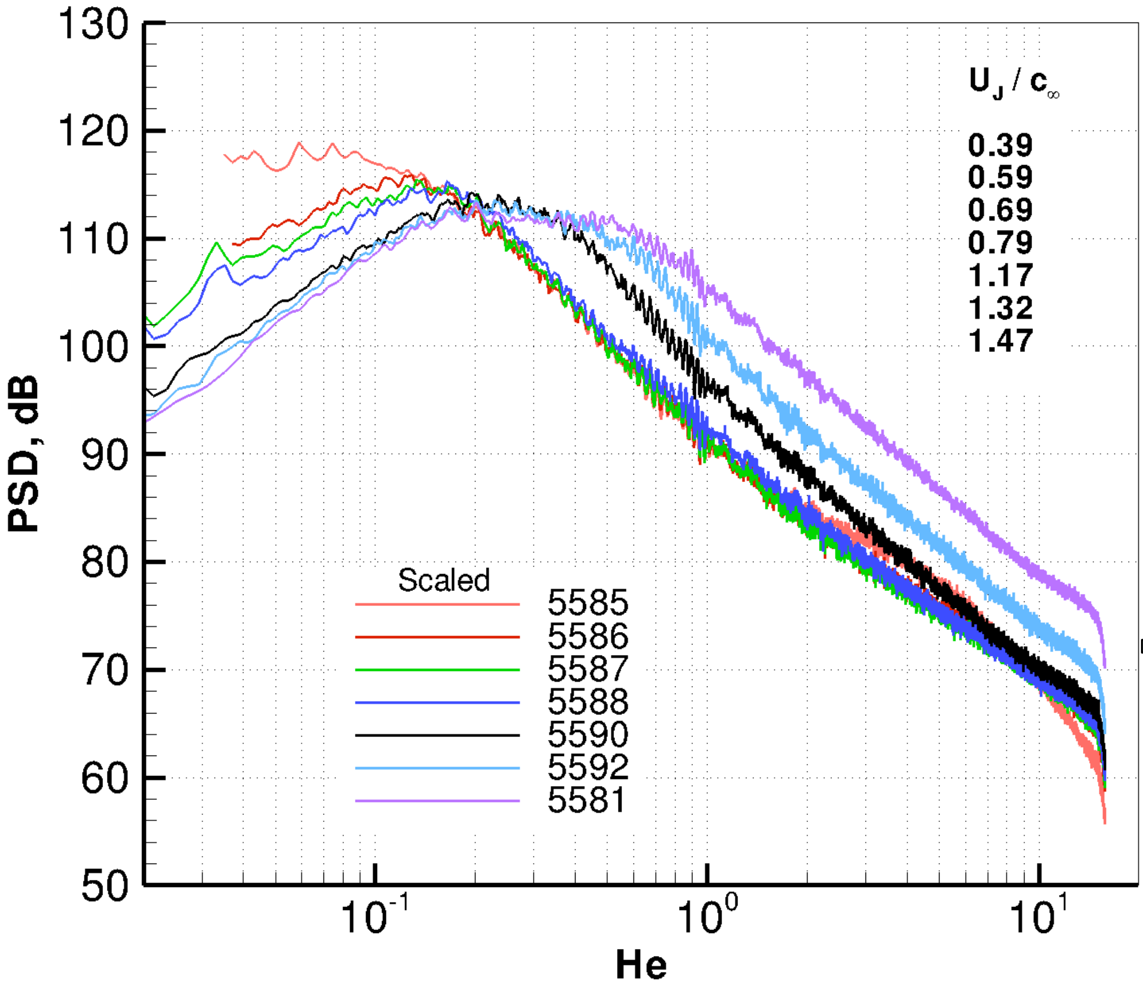
$$T_s = 2.70, \theta = 120^o, n = 6.15$$



Ts = 2.70, θ = 120°, n = 6.15

SCALED SPECTRA

$$T_s = 2.70, \theta = 150^o, n = 8.0$$



smc000

Rdg	U_j/c_∞	M	NPR
5585	0.39	0.24	1.04
5585	0.59	0.36	1.09
5587	0.69	0.42	1.12
5588	0.79	0.48	1.17
5590	1.17	0.72	1.40
5592	1.32	0.81	1.52
5581	1.47	0.91	1.69

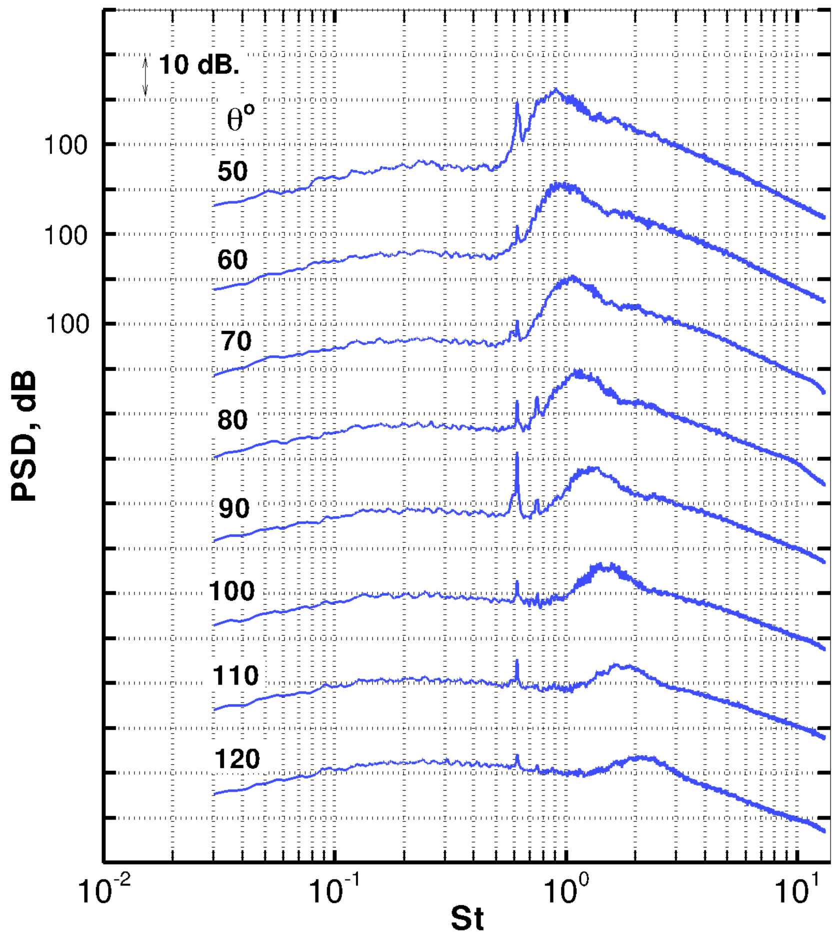
Ts = 2.70, θ = 150°, n = 8.0

NOISE COMPONENTS

- Scaling laws help to identify noise components
  - Jet mixing noise
  - Shock-associated noise
  - Amplification of jet mixing noise due to screech (AMN)
  - Mixing noise (components) at small aft angles

NOISE COMPONENTS

Under-expanded Supersonic Jets
No Screech Amplification

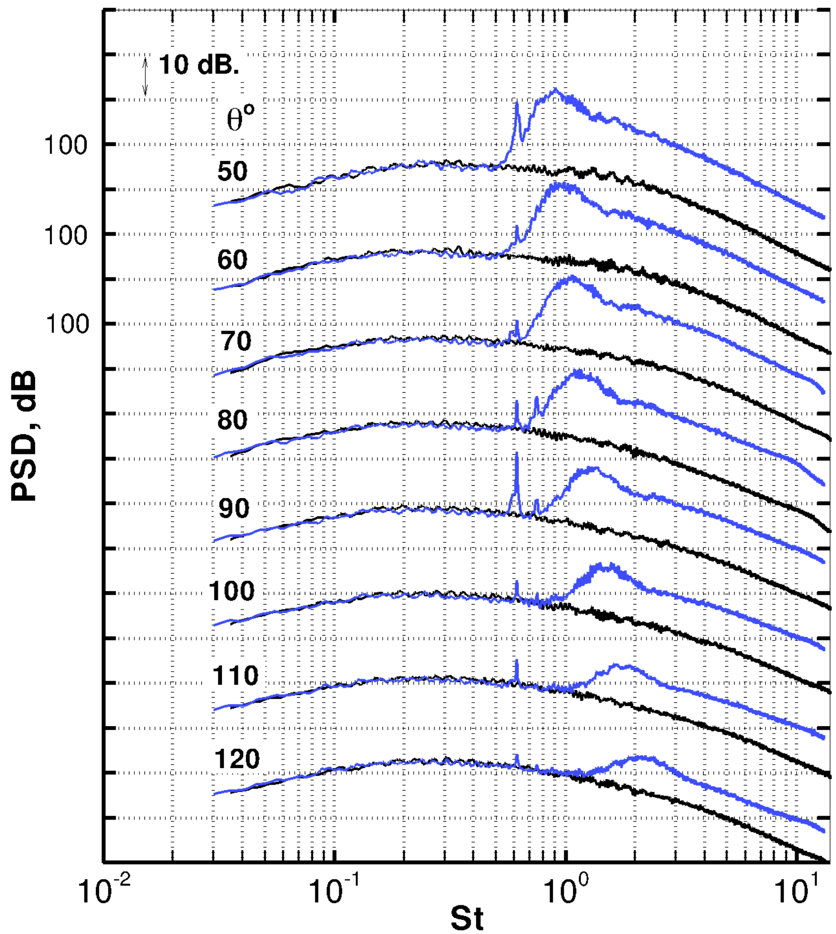


	Rdg	U_j/c_∞	T_t	M_j	M_d	NPR
smc000	1614	0.91	1.0	1.0	1.0	1.89
smc021	1605	1.04	1.0	1.17	1.0	2.33

Rdg: 1605 (Blue); Mixing noise from scaled Rdg: 1614 (Dark)

NOISE COMPONENTS

Mixing Noise – No Screech Amplification

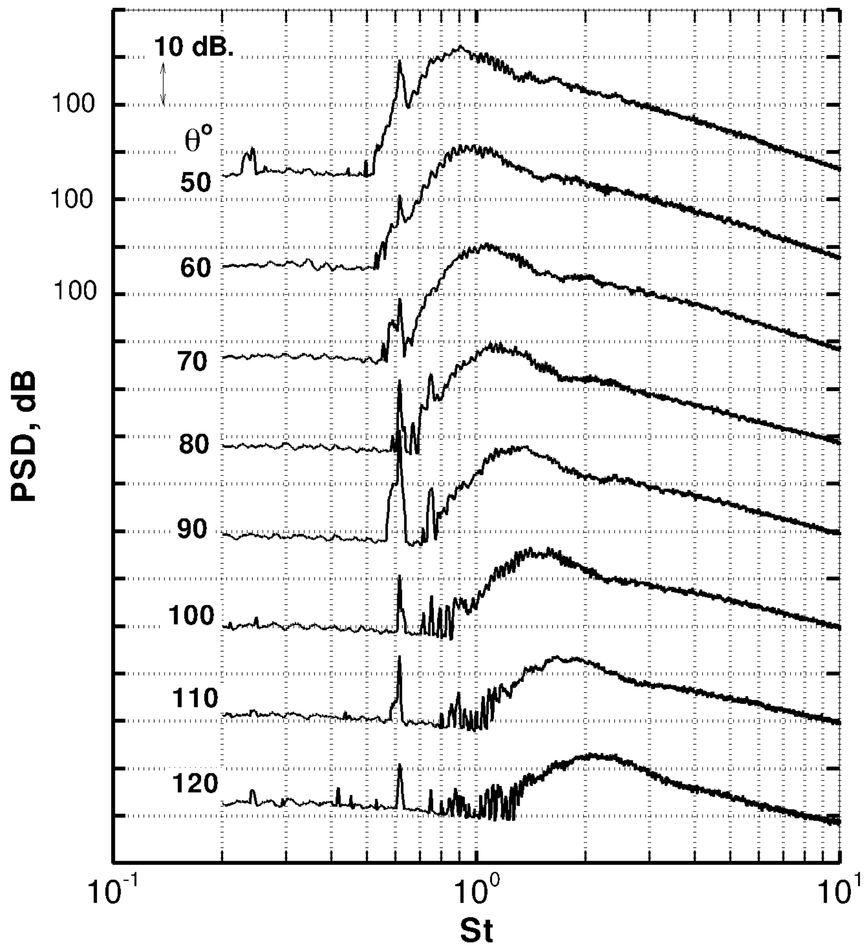


Rdg: 1605 (Blue); Mixing noise from scaled Rdg: 1614 (Dark)

	Rdg	U_j/c_∞	T_t	M_j	M_d	NPR
scaled smc000	1614	0.91	1.0	1.0	1.0	1.89
smc021	1605	1.04	1.0	1.17	1.0	2.33

NOISE COMPONENTS

Shock Noise – No Screech Amplification



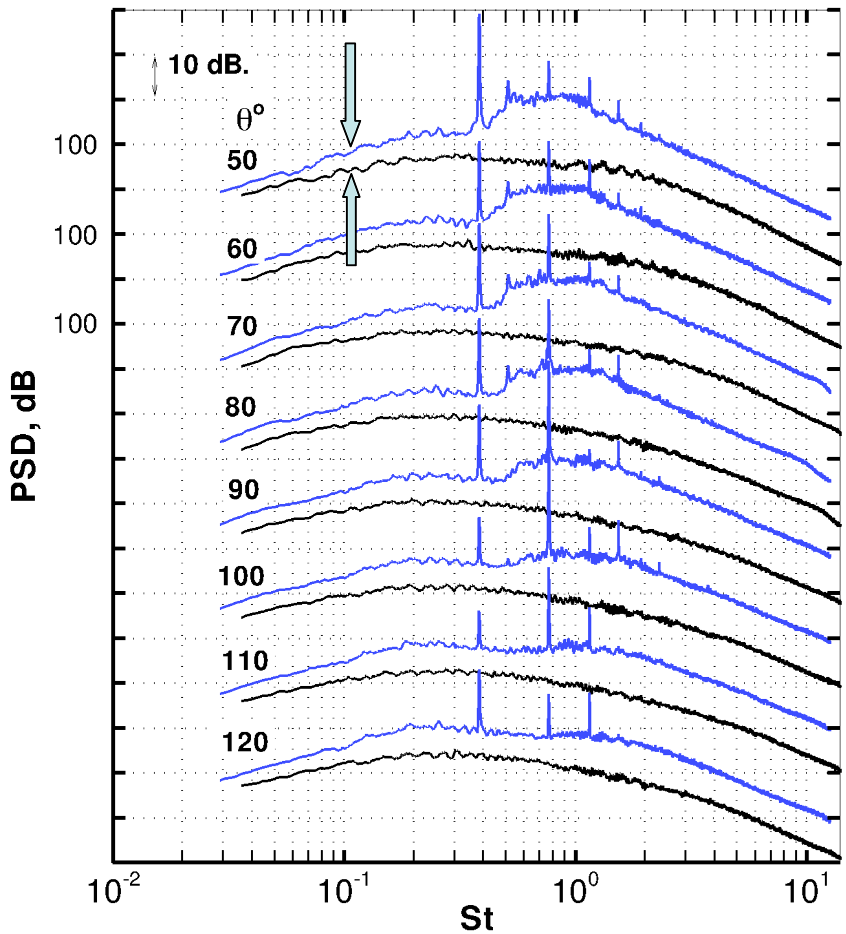
Rdg: 1605 - Shock-associated noise

smc021

Rdg	U_j/c_∞	T_t	M_j	M_d	NPR
1605	1.04	1.0	1.17	1.0	2.33

NOISE COMPONENTS

Under-expanded Supersonic Jets
With Screech Amplification

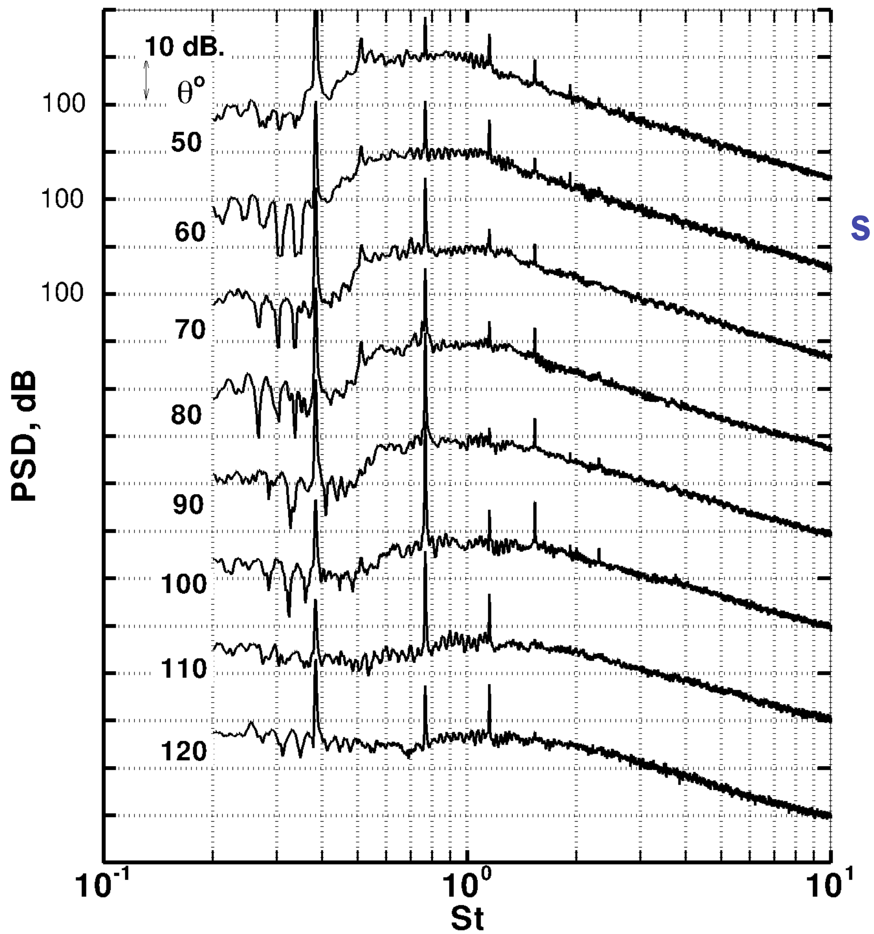


smc000-1616(Blue); Mixing noise from scaled smc000-1614 (Dark)

	Rdg	U_j/c_∞	T_t	M_j	M_d	NPR
scaled smc000	1614	0.91	1.0	1.0	1.0	1.89
smc000 (Uexp)	1616	1.08	1.0	1.24	1.0	2.55

NOISE COMPONENTS

Shock Noise – Screech Amplification



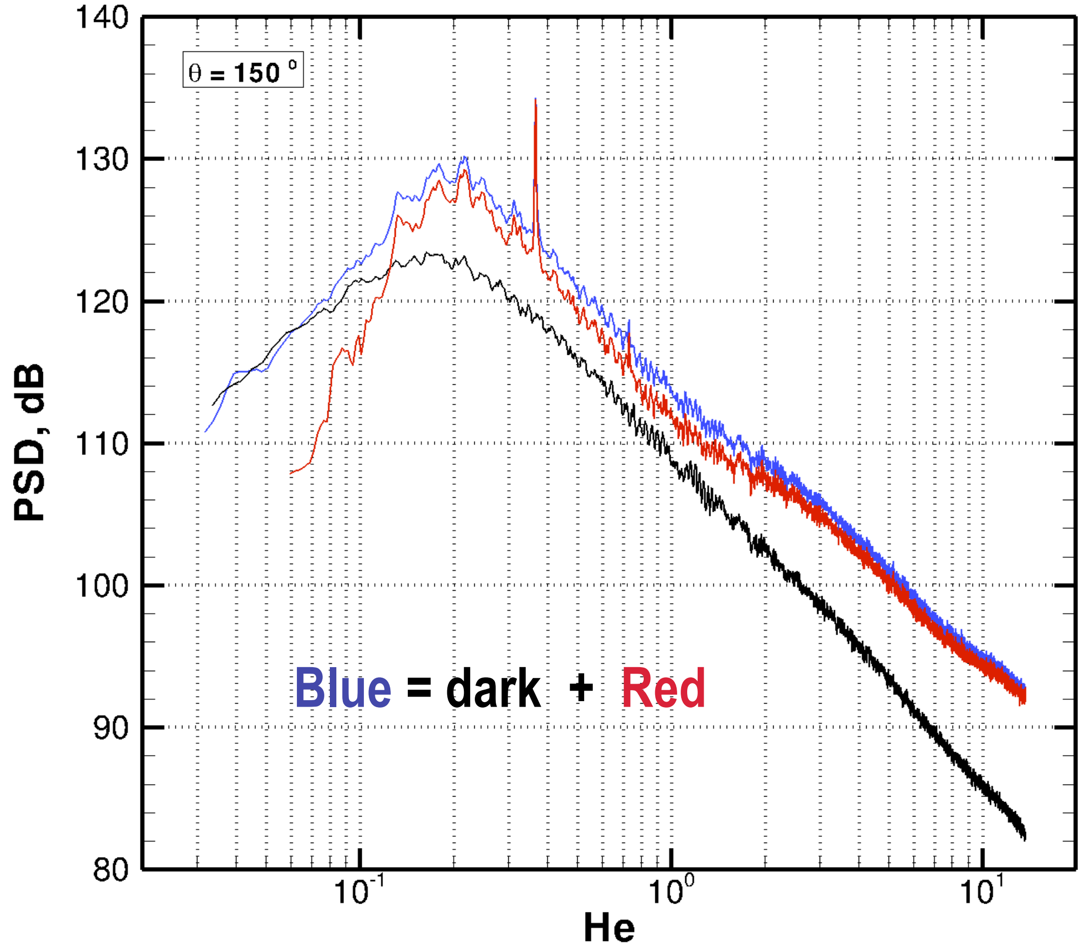
smc000-1616 - Shock-associated noise

smc000 (Uexp)

Rdg	U_j/c_∞	T_t	M_j	M_d	NPR
1616	1.08	1.0	1.24	1.0	2.55

NOISE COMPONENTS

Small Aft Angle – Supersonic Noise Components



	Rdg	U_j/c_∞	M_j	M	NPR
smc000	1614	0.91	1.0	1.0	1.89
smc000	1618	1.23	1.47	1.0	3.51

JeNo PREDICTIONS vs. DATA

JeNo Methodology AIAA-2007-3640

Governing Eq: Linearized Euler

Source: Reynolds Stress + Velocity/Enthalpy

GF: Locally Parallel Mean Flow

Unheated Jets

- Good agreement along sideline angles
- Small aft angle agreements deteriorate with increasing jet velocity (jet spread, instability)

JET CONDITIONS

Subsonic Jets Table 1

Nozzle	SP	Rdg	Ma	Tsr	M	Ttr	NPR
smc000	3	1513	0.50	0.95	0.502	1.040	1.188
	8	1521	0.50	1.00	0.501	1.047	1.188
	163	1525	0.50	1.10	0.476	1.154	1.168
	153	1528	0.50	1.20	0.456	1.251	1.153
	15	1531	0.50	1.43	0.419	1.479	1.128
	5	1514	0.70	0.90	0.724	1.025	1.418
	10	1523	0.70	1.00	0.702	1.10	1.389
	165	1526	0.70	1.10	0.666	1.20	1.346
	155	1529	0.70	1.20	0.640	1.30	1.318
	17	1532	0.70	1.43	0.585	1.53	1.260
	7	1515	0.90	0.85	0.972	1.017	1.834
	12	1524	0.90	1.00	0.90	1.164	1.694
	167	1527	0.90	1.10	0.857	1.26	1.616
	157	1530	0.90	1.20	0.825	1.359	1.563
	19	1533	0.90	1.43	0.751	1.592	1.452
	405	1614	0.91	0.83	1.0	1.0	1.893
	415	1584	1.224	1.50	1.0	1.80	1.893
	425	1572	1.356	1.83	1.0	2.2	1.893
	435	1565	1.50	2.26	1.0	2.70	1.893
	445	1554	1.63	2.70	1.0	3.20	1.893

JET CONDITIONS

Under-Expanded Convergent Nozzles — Table 2

Nozzle	SP	Rdg	Ma	Tsr	Mj	Ttr	NPR
smc000	8020	1534	1.18	1	1.18	1.28	2.38
	8030	1537	1.40	1.40	1.18	1.79	2.38
	8060	1539	1.80	2.37	1.18	2.99	2.34
	9020	1535	1.40	1	1.40	1.39	3.19
	9050	1538	1.80	1.665	1.40	2.30	3.17
	12040	1541	1.80	1.0	1.80	1.65	5.76
	12070	1540	2.40	1.795	1.80	2.92	5.71

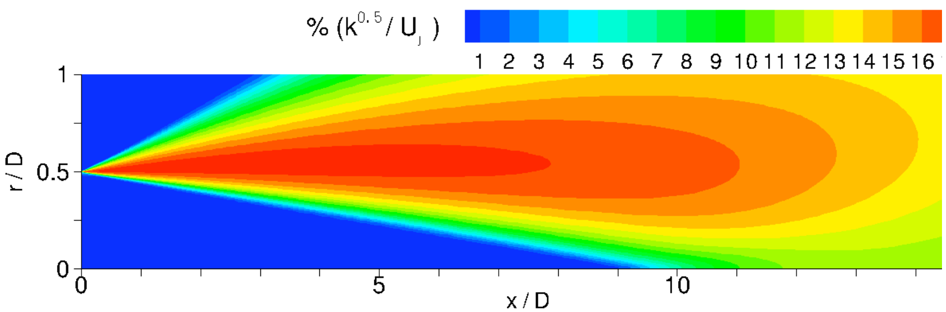
Ideally Expanded Supersonic Jets — Table 3

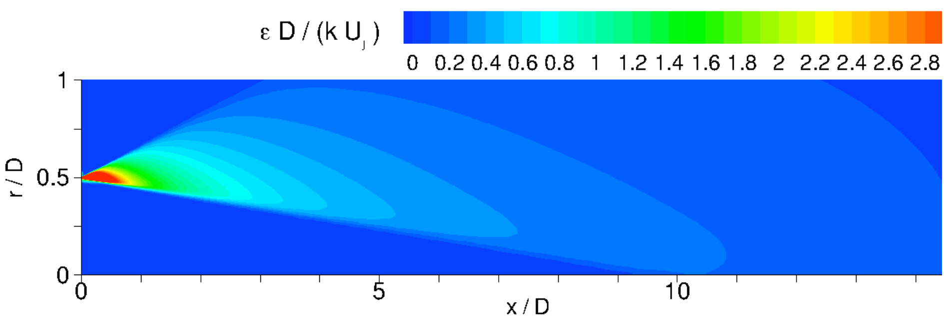
Nozzle	SP	Rdg	Ma	Tsr	Md	Ttr	NPR
smc014	8020	1655	1.18	1	1.18	1.28	2.38
	8030	1656	1.40	1.40	1.18	1.79	2.38
smc015	9020	1660	1.40	1	1.40	1.39	3.19
	9050	1661	1.80	1.665	1.40	2.30	3.17
smc016	10010	1645	1.25	0.695	1.50	1.0	3.67
	10030	1646	1.50	1.0	1.50	1.45	3.67
	10060	1647	1.80	1.446	1.50	2.09	3.70
smc018	12040	1651	1.80	1	1.80	1.65	5.76
	12070	1653	2.40	1.795	1.80	2.92	5.71

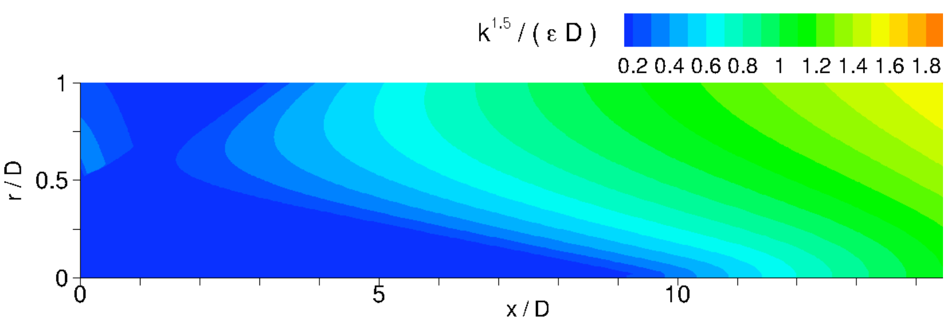
WIND-RANS

TKE, Time & Length Scales

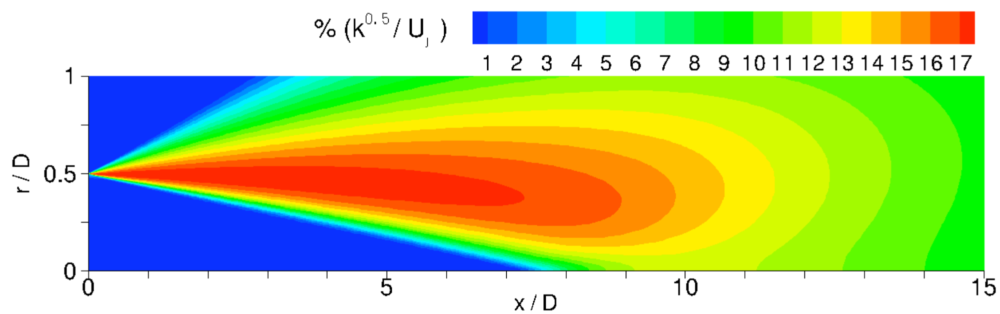
smc000-1614 (M =1.0, M_a = 0.91, T_r = 1.0)

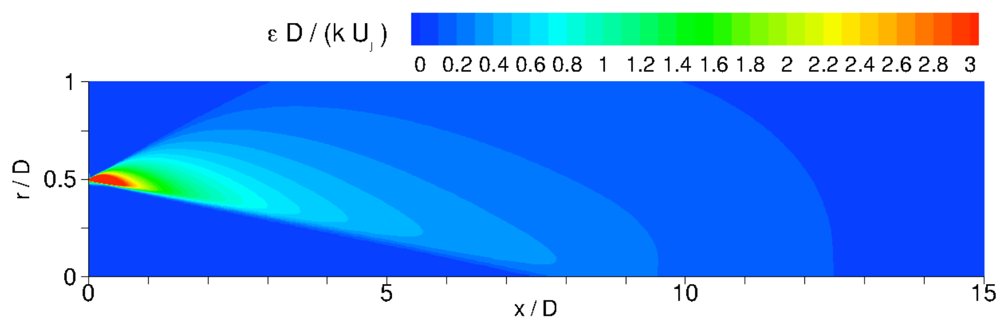


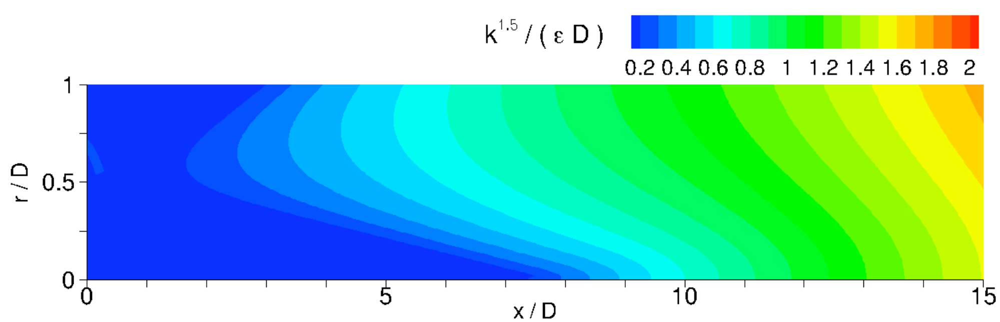




smc000-1554 (M = 1.0, M_a = 1.63, T_r = 3.2)



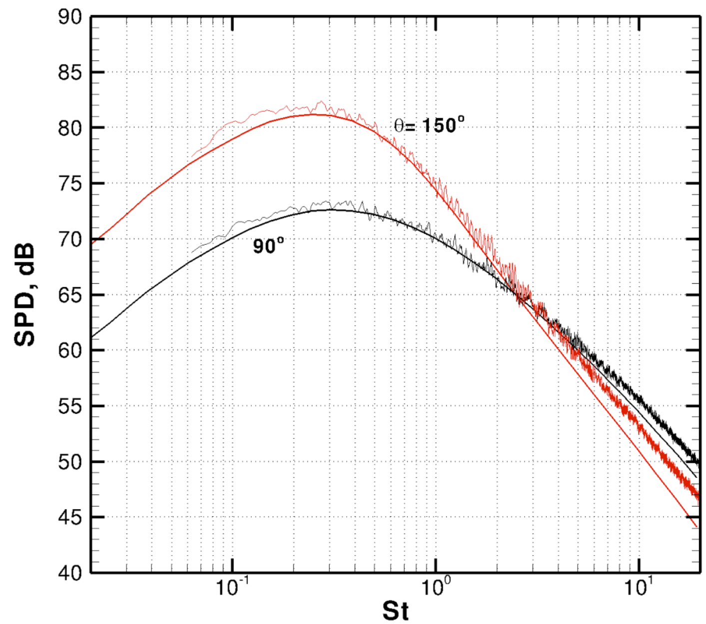


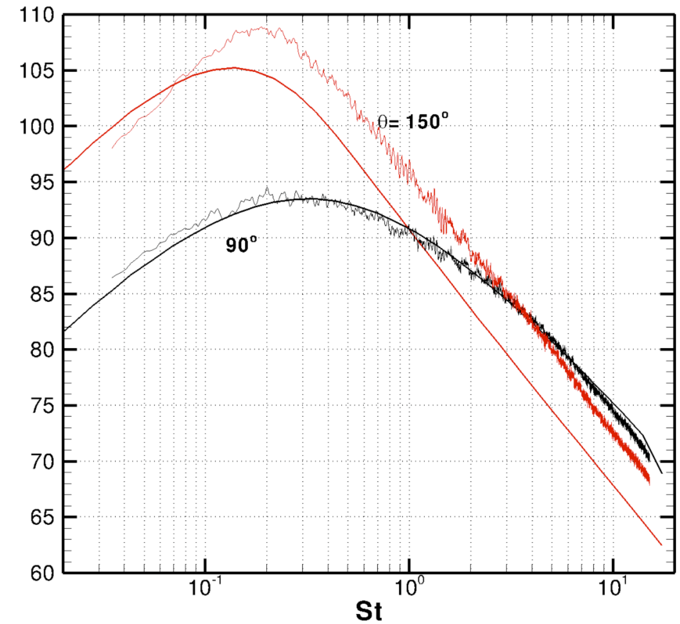


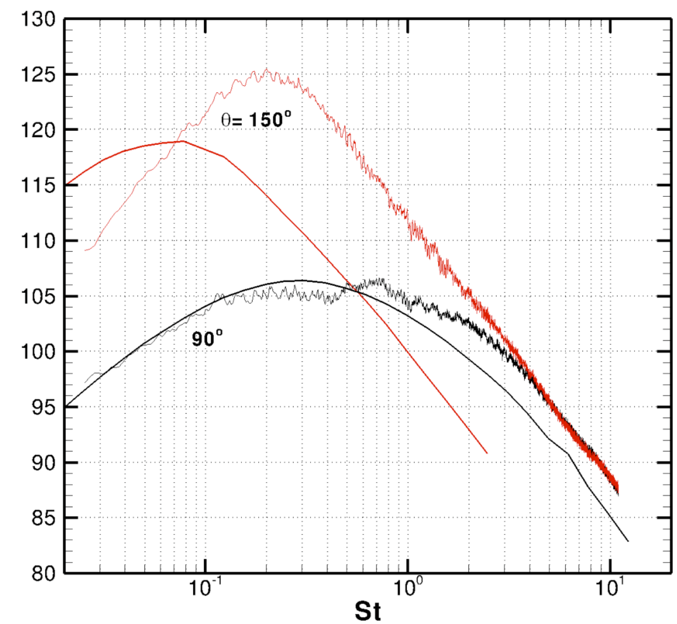
JeNo PREDICTIONS vs. DATA

Unheated Jets $T_t = 1.0$

Subsonic	*Subsonic*	*Supersonic (smc016)*
$M = 0.502$	$M = 0.97$	$M = 1.50$ (CD)
$M_a = 0.50$	$M_a = 0.90$	$M_a = 1.25$



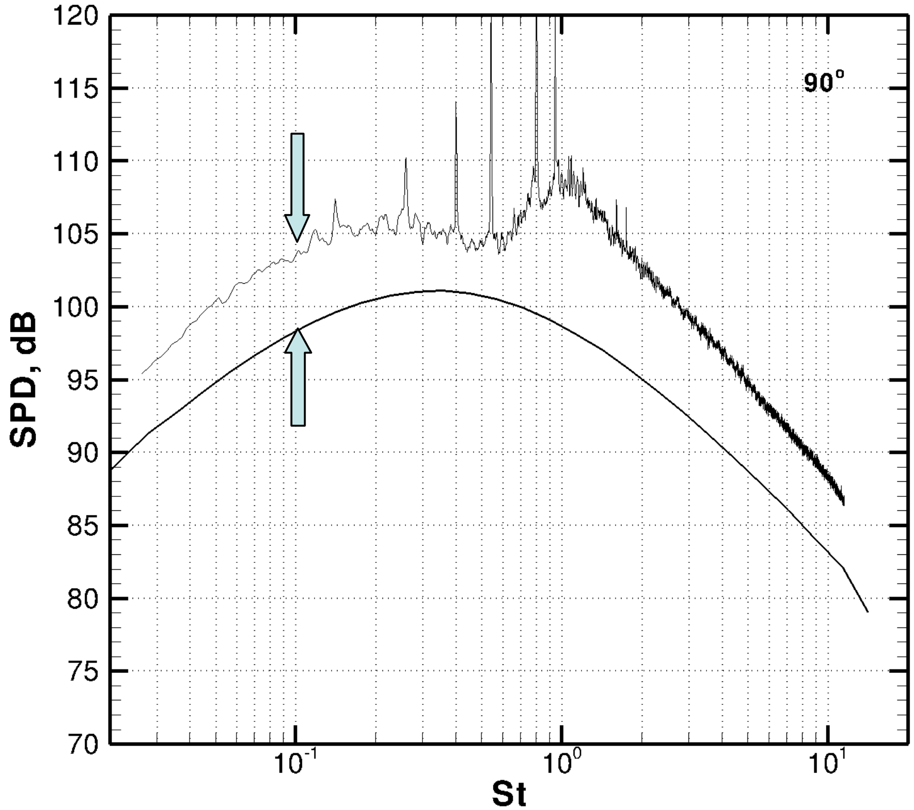




JeNo PREDICTIONS vs. DATA

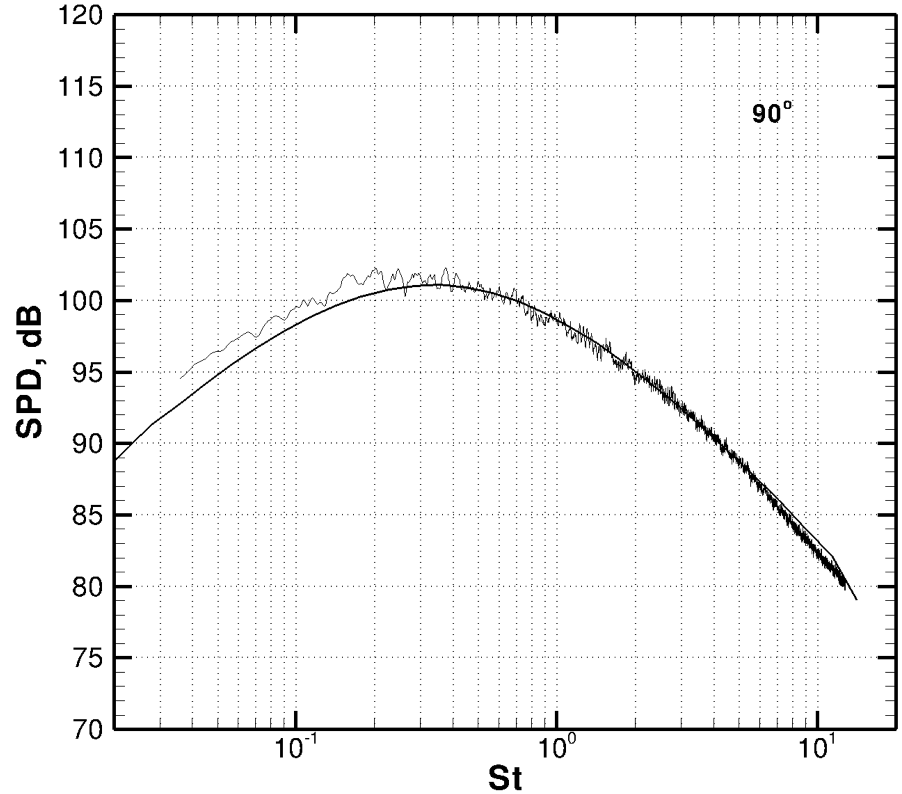
Rdg	U_j/c_∞	T_s	M	NPR
1534	1.18	1.0	1.0	2.38
1524	0.90	1.0	0.90	1.69

Data with Screech Amplification (smc000-1534)



JeNo vs. SHJAR DATA
smc000-1534 shajar data vs jeno,

Supersonic data corrected for AMN effect (scaled up smc000-1524)

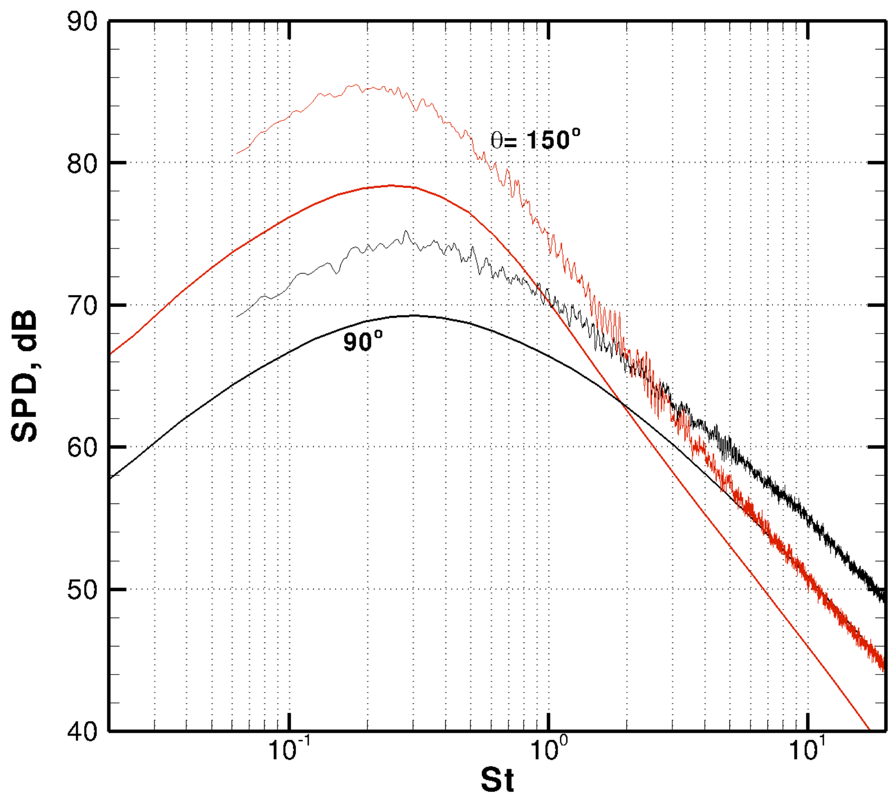


JeNo vs. SHJAR DATA
smc000-1534 jeno predictions vs scaled smc0024 shjar data (n = 7.57, 9.27) at (90, 150deg)

JeNo PREDICTIONS vs. DATA

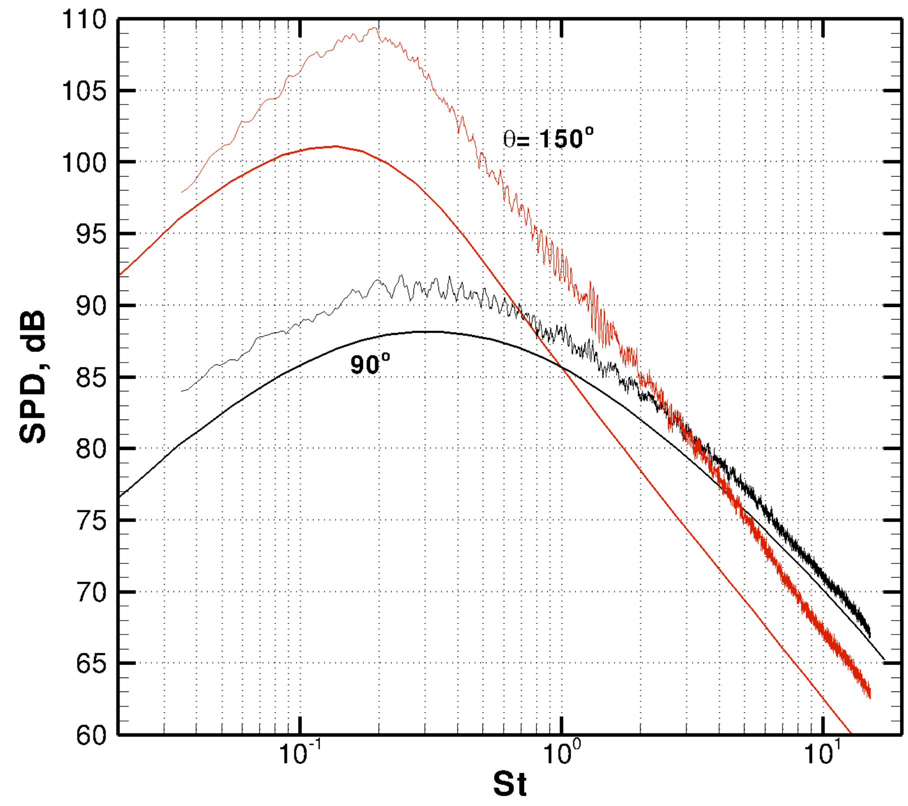
Hot Jets (Excludes Enthalpy Source Term)

$M_a = 0.50,\ T_r = 1.43$



JeNo vs. SHJAR DATA
smc000-1531 Lossless, NB spectral density on ARC = 100D, angles are from inlet

$M_a = 0.90,\ T_r = 1.43$

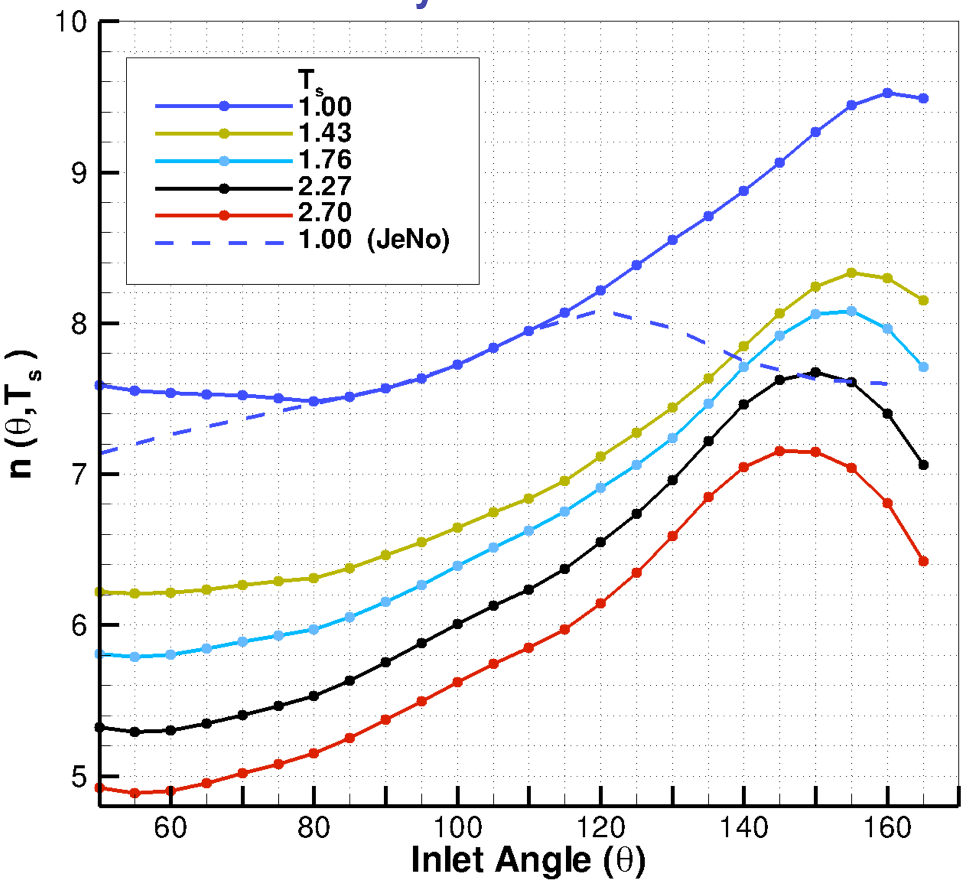


JeNo vs. SHJAR DATA
smc000-1533 Lossless, NB spectral density on ARC = 100D, angles are from inlet

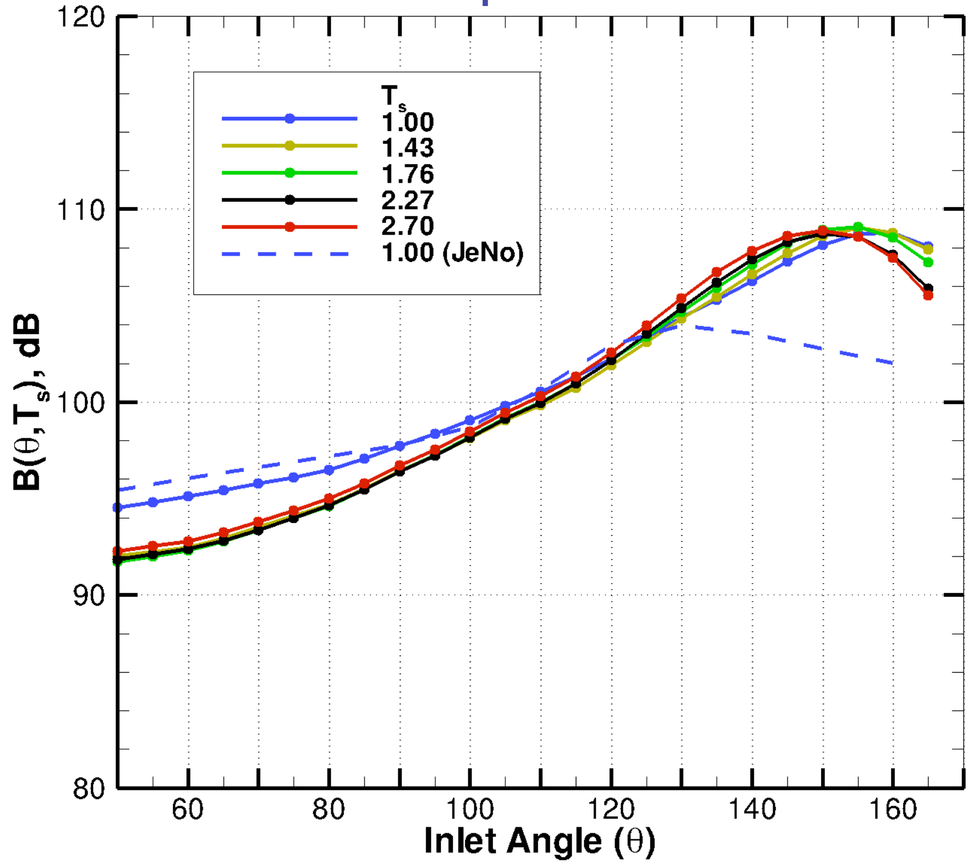
JeNo Power Factors

(T_s = 1.0)

Velocity Power Factor



Intercept Parameter



SUMMARY

Wind (CFD) Based JeNo Predictions

- Good agreement along sideline (unheated $T_s \leq 1$)
- Deteriorating agreement at small aft angles with increasing jet speed resulting in HF cutoff (Jet Spread ; Instability Noise)
- Deficit in predicted PSD in the absence of heat-related sources.